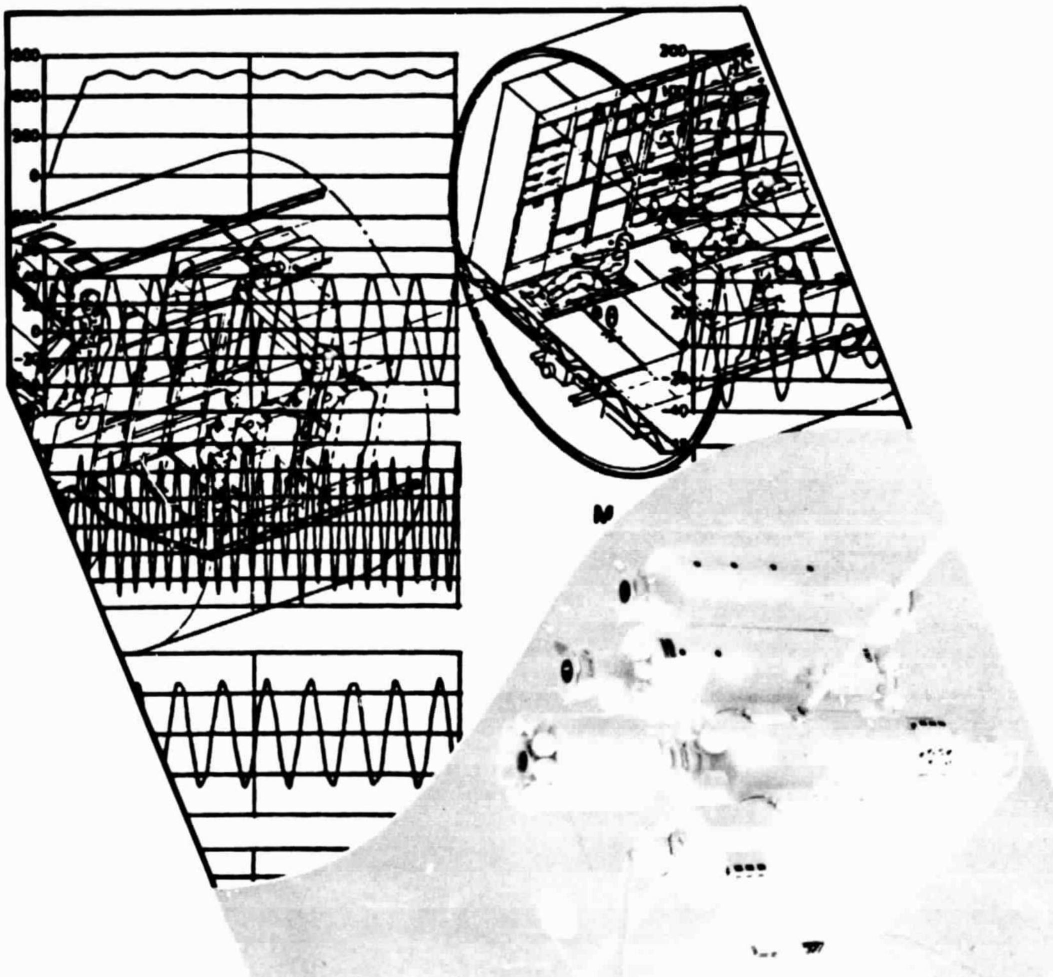
Final Report Volume I
Executive Summary
D483-10012-1

Space Station Systems Technology Study

(Add-on Task)



(NASA-CR-171415) SPACE STATION SYSTEMS TECHNOLOGY STUDY (ADD-ON TASK). VOLUME 1: EXECUTIVE SUMMARY Final Report (Boeing Aerospace Co., Huntsville, Ala.) 105 p HC A06/MF A01 CSCL 22B G3/15

N85-22459

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SPECTRA RESEARCH SYSTEMS (SRS)

February, 1985

D483-10012-1

SPACE STATION SYSTEMS TECHNOLOGY STUDY
(Add-on Task)

Final Report

VOLUME I

EXECUTIVE SUMMARY

D483-10012-1

Conducted for NASA Marshall Space Flight Center

Under Contract Number NAS8-34893

February 1985

Boeing Aerospace Company

Spectra Research Systems

FOREWORD

This Space Station Systems Technology Study add on task (Contract NAS8-34893 S/A 6) was initiated in June 1984 and to be completed in February 1985. The study was conducted for the National Aeronautics and Space Administration, Marshall Space Flight Center, by the Boeing Aerospace Company with Spectra Research Systems as a subcontractor. The study final report is documented in three volumes.

D483-10012-1	Vol. I	Executive Summary
D483-10012-2	Vol. II	Trade Study and Technology Selection Technical Report
D483-10012-3	Vol. III	Technology Advancement Program Plan

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LIST OF ACRONYMS AND ABBREVIATIONS

ACCEL	remote body station 1501
ACOR	body station 100
ACS	attitude control subsystem
AFB	Air Force Base
AI	artificial intelligence
APSTS	Advanced Platform System Technology Study
ATP	authorization to proceed
BAC	Boeing Aerospace Company
BIT	built in test
BITE	built in test equipment
C&D	controls and displays
CAD	computer aided design
CAE	computer aided engineering
CDG	Concept Development Group
Cg	center of gravity
CG and IM	center of gravity and inertial momentum
CGI	computer generated imagery
CMG	control moment gyro
GN_2	nitrogren gas
CO_2	carbon dioxide
CP	co-pilot
CPU	central processor unit
CRT	cathode ray tube
DARPA	Defense Advanced Research Projects Administration
dc/ac	direct current/alternating current
DEC	Digital Equipment Company
deg/sec	degrees per second
DMS	data management subsystem
DoD	Department of Defense

EASY	Engineering Analysis System
EC/LSS	Environmental Control/Life Support Subsystem
EL	Electroluminescent
EPS	Electrical Power Subsystem
ES	expert system
EVA	extra vehicular activity
FAB	fabrication
FO	fiber optics
FF	Free Flyer
ft	feet
FY	fiscal year
GL/EP	glass/epoxy
GN&C	guidance, navigation and control
GR/EP	graphite/expoxy
GPS	global positioning system
GSFC	Goodard Space Flight Center
GSTDN	Ground Station Tracking Data Network
HOL	higher order language
HR	hour
H_2O	water
HUD	head up display
Hz	Hertz (a measure of frequency)
IAC	integrated analysis capability
IC	integrating controller
I.D.	inside diameter
IEEE	Institute of Electrical and Electronic Engineers
INDA	interface from NASTRAN dynamics analyzer
INTF	interface
I/O	input/output
IOC	initial operational capability

JPL	Jet Propulsion Laboratories
JSC	Johnson Space Center
KG	kilograms
KW	kilowatts
LAN	local area network
lb	pounds
lbm	pounds-mass
LCD	liquid crystal display
LCLV	liquid crystal light valve
LED	light emitting diode
LeRC	Lewis Research Center
LIOH	lithium hydroxide
LISP	list processor
LR	line replaceable
MACLISP	Macro Lisp
MBPS	million bits per second
MHz	megahertz
MIL-STD	military standard
MIPS	million iterations per second
MMH	Monomethyl Hydrazine
MPA	multi-beam phased array
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structure Analyzer
NIU	network interface unit
n-m-sec	Newton-meter-seconds
NOS	network operating system
NRZ	nonreturn to zero
ns	nanoseconds

O&C	operations and checkout
O.D.	outside diameter
OMV	orbital maneuvering vehicle
OPS4	an expert system development tool
ORACLS	optimum regulator and control of linear systems
ORU	orbital replaceable unit
C/O	check out
OSI	operator system interface
OTV	orbital transfer vehicle
P	pilot
PDP	model designator for line of DEC computers
P/L	pay load
PRLCH	pre launch
PSI	pounds per square inch
Psia	pounds per square inch absolute
Psid	pounds per square inch differential
Pwr	power
QWERTY	Top left hand row of keys on a typewriter
R&D	research and development
RCA-PRICE	Radio Corporation of America Price Modeling Program
RCS	reaction control system
RF	radiofrequency
RI	name of expert system to configure VAX installations
RMS	remote manipulator system
ROM	read only memory
R/T	receiver-transmitter
RTOP	research technology objectives and plans
SAR	synthetic aperture radar
Sec	second

SEPS	solar electric propulsion spacecraft
SOA	state of art
S/C	spacecraft
SRI	Stanford Research Institute
SRS	Spectra Research Systems
SS	Space Station
STS	space transportation system
TBD	to be determined
TCS	thermal control system
TDMA	time division multiple access
TDRSS	tracking and data relay satellite system
TFEL	thin-film electro luminescent
TI	Texas Instruments
TMS	teleoperator maneuvering system
TVC	thrust vector control
VAX	virtual address extension
VHSIC	very high speed integrated circuit
VLSI	very large scale integration
VM	ventilator manager
XCVR	transceiver

1.0 INTRODUCTION

This is the Executive Summary, volume I, of the final report for the Space Station Systems Technology Study add-on task. The study has been conducted for the Marshall Space Flight Center (MSFC) by the Boeing Aerospace Company (BAC) and Spectra Research Systems (SRS). The overall study objective is to identify, quantify, and justify the advancement of high-leverage technologies for application to the early space station. Research plans were developed for each of the selected high-leverage technologies. The objective was fulfilled through a systematic approach tailored to each of the technology areas studied.

The current Space Station Systems Technology Study add-on task was an outgrowth of the previous segments of the Advanced Platform Systems Technology Study (APSTS). The previous segments were completed in April 1983 and February 1984 for the MSFC by the Boeing/SRS team. The initial study segment proceeded from the identification of 106 technology topics. Of those topics, five were selected for detail trade studies. The technical issues and options of those five were evaluated through detailed trade processes during the initial study. Individual consideration was given to costs and benefits. Advancement plans were subsequently developed for the five topics. A similar approach was used in the second study segment with emphasis on system definition in four specific technology areas out of the initial five. In the current add-on task two of the initial five areas have been examined further to expand the definition of the concepts and one new area has been added to cover a function emphasized by emerging Space Station operational definitions.

The three study areas addressed in the add-on task are: (1) autonomous functional control of Space Station subsystems, (2) the impact from structural dynamic motions on Space Station attitude control, and (3) controls and displays for OMV, OTV, and spacecraft servicing, flight operations, and functional operation. The first two areas are extensions of areas identified during the previous study segments. They were conducted to facilitate a more in-depth understanding of the technology issues. Different study approaches were used for each of the three study areas. System concepts were studied in the autonomous functional control task. In addition to conducting investigations of an

autonomous functional controller at a greater level of detail, this add-on task considered additional subsystems: guidance, navigation and control; local data management, and communications. For the attitude control study add-on task the principal methodology was to simulate the Space Station dynamics with various models of disturbances and to use that simulation to evaluate various control system concepts. The controls and displays study was a new task and therefore contained more basic definition information as part of the technology need assessment. Each of the approaches produced useful advancements in the understanding of technology issues and development needs. The summary discussions are presented in the following sections.

The overall study was divided into three tasks. During task 1, the design concepts in each of the three study areas were refined. The concepts were used to annunciate specific technology options upon which comparative studies were conducted. Candidate high-leverage advancement technologies were then selected from the options. The cost, benefits, schedules, and life cycle costs for each of the options were evaluated in task 2. Selection of the technology advancement items was made during this latter task. Technology advancement plans were prepared for each of the selected items in task 3. The overall study task flow is shown in figure 1.0-1.

This volume presents a summary of the work performed to select the high leverage items. The total final report is made up of this volume, Volume II: Trade Study and Technical Selection Technical Report, and Volume III: Technology Advancement Program Plan. More detailed discussion of the trades conducted and the technology advancement plans are given in volumes II and III respectively.

1.1 TECHNOLOGY SELECTIONS AND RATIONALE

Twelve potential technology advancement items were identified during this study. These items were analyzed and evaluated in task 2, considering technical as well as cost benefits and schedule criteria. Study plans were prepared for six of the selected high leverage items. The items selected for planning are:

a. Development of effective models to support an automated integrating controller.
b. Development of technology to interface expert systems with conventional software.

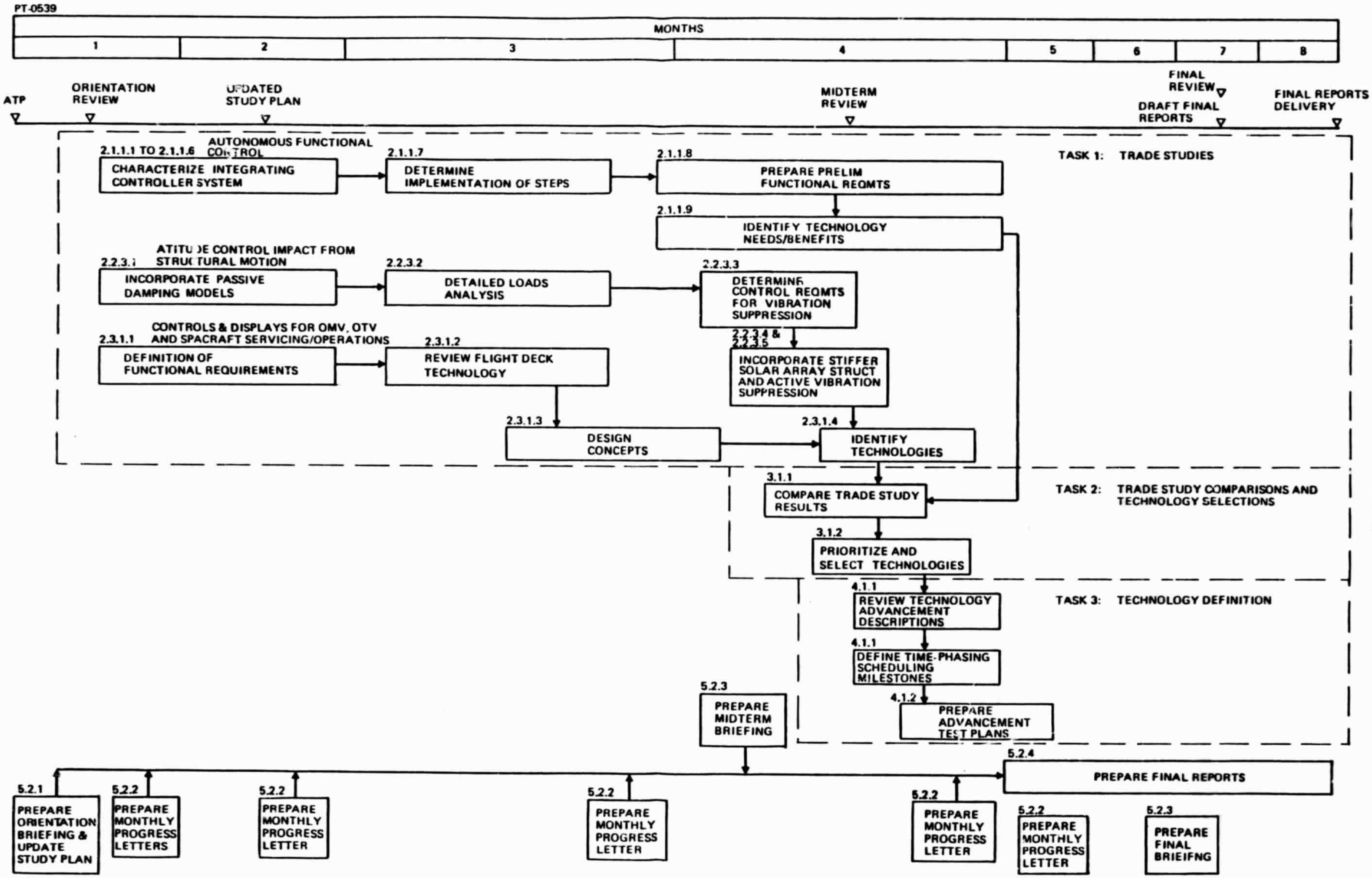

Figure 1.0-1. Study Plan Flow Diagram

c. Space qualified inferencing processor development for an integrating controller.

d. Very wide field of view head-up display development for control stations.

e. High performance color flat panel LCD display development.

f. Development of high performance color programmable multifunction switches.

The following sections summarize the rationale associated with selections made in each of the three study areas.

1.1.1 Autonomous Functional Control Rationale

An automation and robotics philosophy has been established as a goal for the space station. This philosophy calls for the initial space station to evolve to a nearly autonomous facility within a number of years after orbital operations begin. This philosophy is in agreement with the needs of a Space Station to provide a facility for a wide range of missions without encumbering the crew (or mission controllers) with excessive hours for station upkeep. This philosophy is also in agreement with the needs for efficient and balanced operation of the Space Station's complex systems over extended lifetimes with limited consumable and power resources. Autonomous functional control is justified because it provides subsystem management for a long life, allows space station functions to evolve, and enables the crew to do productive experimental and/or operational work. The rationale for this kind of control is that it provides the decision making functions that would otherwise be left to mission ground controllers and astronauts. The processes involved in developing the integrating controller to implement autonomous functional control drive out needs for advancements in artificial intelligence software, space qualified data processing equipment, sensors, actuators, and devices for interacting with the crew. Because the development lead times are long for many of these advancements, there is an urgency for starting advancement programs for the integrating controller technologies as soon as possible.

The cost benefits assessment of this study modify the conclusions of the previous study because of the expectation of supporting advancements from the DARPA Strategic Computing Study. These expectations have reduced the advancement costs for technologies that have generic characteristics. The benefits were not modified from those

developed during the previous study because no new information on benefits was uncovered. The result was that the benefits versus cost ratio improved and was also partitioned over the several technology advancement candidates. Table 1.1-1 gives the benefits versus cost ratios estimated for five technology advancement candidates identified for autonomous functional control. These candidates include the three that were planned for development as discussed in volume III. Table 1.1-2 gives the prioritization of the five candidates based on three unweighted criteria elements. Note that the real time expert system development and knowledge engineering development were considered to be sufficiently generic so that DARPA results would provide sufficient advancement support.

1.1.2 Attitude Control Rationale

The objective of the add-on task study in attitude control was to extend the efforts of the previous studies to include; symmetric mode analysis, elemental structure damping, active controller evaluation, and incorporation of stiffer structure in the solar array design. Accordingly, a detailed evaluation of space station control and dynamic performance in the presence of structural interaction excited by orbiter berthing operations and crew activity was performed. Control requirements for the symmetric modes were derived and motion of the flexible appendages was studied in detail. The uncontrollable modes identified in the previous study phase were controlled by selected techniques including passive and active stabilization. Passive stabilization of solar array torsional vibration focused on the design of discrete viscous damping mechanisms in the astromast structure. Active torsional vibration suppression considered the use of the beta tilt and sun tracking actuators. Variations to the existing structural configuration considered alternate solar array deployment schemes which offer substantially stiffer structures in torsion.

The conclusions of the study can be summarized as follows. Generally it is recognized that attitude performance requirements for a habitable Space Station in low earth orbit are lax. This study has clearly demonstrated that when the control bandwidth is small compared with the bandwidth of the sensors and actuators, all modes in the proximity and above the controller pass band are effectively gain stabilized. Thus robustness

Table 1.1-1 Autonomous Functional Control Candidates
Benefits/Cost Ratios

	Candidate	Benefits/Cost Ratio
1.	Adapting expert systems to real time operations	37.5
2.	Developing expert systems that interface well with conventional software	12.5
3.	Developing effective simulation models	6.0
4.	Developing knowledge engineering techniques	4.17
5.	Space Qualified Compact LISP Computer	2.0

Table 1.1-2 Prioritized Autonomous Functional Control
Technology Candidates

Candidate	Sched	Use	Benefit/Cost	Combined
Expert systems that interface well with conventional S/W	1	2	2	5
Adapting Expert Systems to Real Time Operations	4	1	1	6
Simulation Modeling	2	3	3	8
Knowledge Engineering Tech.	5	4	4	13
Space Qualified LISP Computer	3	5	5	13

(stability with a margin) is guaranteed under these conditions and the fundamental issue becomes one of augmenting uncontrollable modes when such augmentation is deemed necessary. The study has shown that coordinated control using collocated sensors and actuators will provide effective vibration suppression In this particular application it was shown that CMG control of the central modular core in conjunction with the panel positioning actuators gives vibration suppression for all modes, with the exception of the symmetric bending modes. Worse case amplitudes of appendage motion due to symmetric bending was found to be negligible. Based on these observations it is concluded that attitude control development for Space Station is not significantly influenced by flexibility. The need for a dedicated vibration suppression system is eliminated by collocated and coordinated regulation of modular core and solar array motion. However, preference toward a locked panel tilt actuator may require some passive damping to dissipate solar array torsional vibrations especially in the case where SEPS type arrays and deployment are utilized. If a type of stiff substrate backed panel or equivalent is employed, then the severity of the vibration problem is mitigated, if not totally eliminated. In this case, one need only insure that stiffness of the supporting structure is adequate.

1.1.3 Controls and Displays for OMV, OTV and Spacecraft Rationale

The area of controls and displays is a new one to the Space Station Systems Technology Study. It was selected as an area of concern due to its inherent complexity, numerous interfaces and vital function to the safe operation of Space Station. Since it is rapidly advancing, the Station could benefit from the technology by directing that advancement for its own needs.

Based on the developed mission scenario and functional analysis, a minimum of two operators is required to successfully complete the mission. To assist the operators, an expert system is also required to monitor subsystem status of the OMV and RMS, monitor enroute progress of the OMV on its mission, and control the caution and warning system.

The following technologies were found to best satisfy Space Station workstation requirements but require further advancement:

- Liquid crystal display technology for use in both multifunction displays and programmable switches. Beside the numerous Space Station benefits, this technology would also benefit the consumer market and high-technology areas.

- Six-axes hand controller. This technology requires further testing, especially in a zero-gravity environment.

- Voice recognition and synthesis technology. There is a potential benefits interaction with military and commercial development. It may become the favored means of computer interface.

- Wide field of view head-up display. A need must be established yet.

The following technologies were found to satisfy Space Station workstation requirements and do not require further advancement but do require zero-gravity testing:

- Touch pen or screen
- Dedicated switches
- LED programmable switches

2.0 TECHNICAL SUMMARIES

This section summarizes the results of the trade study and technology advancement planning efforts conducted for the Space Station System Technology Study add-on task.

2.1 INTRODUCTION

The trade study effort characterized system concepts in order to define cost versus benefits for autonomous functional control and for controls and displays for OMV, OTV, and spacecraft servicing and operation. The attitude control topic focused on characterizing the Space Station attitude control problem through simulation of control system responses to structural disturbances. The first two topics, mentioned above, focused on specific technology items that require advancement in order to support an early 1990s initial launch of a Space Station, while the attitude control study was an exploration of the capability of conventional controller techniques.

The characterization studies for the autonomous functional control and attitude control were structured to start with the issues identified in the previous segments of the Advanced Platform System Technology Study. Those studies led to a detailed characterization of the topics. The controls and display area was developed for this add-on task based on a mission need model and this led to definitions of various concepts needed to implement those missions. A definition of concepts based on Space Station needs and constraints was developed for each of these areas as an initial step in the current study. These concepts were based on requirements that were derived from Space Station related documentation or from requirements known to exist for similar missions. The next step was to develop the characterizations to identify options within the trade topics. Based on life cycle costs and benefits, or in the case of attitude control performance results, the options were evaluated and technologies necessary to support the more promising options were identified.

Cost and schedule factors related to advancing the technologies recommended in the autonomous functional control and controls and displays areas are also summarized in this section.

The three study topics are presented in this final report in the order that was established by the RFP. That order is autonomous functional control first, then attitude control, and lastly, controls and displays for OMV, OTV and spacecraft servicing and operations. A

summary of the study approaches and results of the three topics is presented in this volume. Detail trade study technical information is in volume II, and detailed advancement planning information is provided in volume III.

2.2 AUTONOMOUS FUNCTIONAL CONTROL

In the previous technology studies, an integrating controller for automated housekeeping subsystems has been identified and characterized as a prime area for technology advancement to support the Space Station. This study extends the systems analyses to characterize the functions of an integrating controller at a level of detail which will allow initial functional requirements to be defined. In addition to extending the systems analysis to greater detail, the study has been expanded to cover more of the subsystems which will be automated on the Space Station. In particular, the guidance, navigation and control, communications, and data management subsystems will be added to the electrical power and thermal control subsystems considered in the previous study phases. The life support subsystem automation has been considered significantly in the previous studies and will not be analyzed further in this add-on study.

2.2.1 Approach

Three housekeeping subsystems of the Space Station were considered in the previous phase of the study which were primarily based on generic subsystem descriptions. The integrating controller functional definitions which were a result of the previous study phase indicated that the process should cover subsystems other than the three which had been considered. For these reasons, a review of subsystem descriptions for the Space Station was conducted as a first step in this expanded study. In performing this first step, each of the five subsystems considered; guidance and control, electrical power, communications, thermal control and data management, were described. The descriptions were based on Space Station subsystem information from results of previously completed Space Station configuration studies, and from experience held by subsystem engineers who were interviewed.

A listing of subsystem functions to be automated was then developed to a level of detail where the control parameters are sensed. Emphasis was placed on identifying subsystem state controlling functions rather than the individual closed loop functions such as those for feedback attitude control. An example of such state controlling functions is the state of control moment gyro wheel inertia loading for attitude control. Control of such

functions requires integration with respect to other entities on the Space Station. The development of an integrating controller concerns these functions.

Once the subsystem function had been developed, a systems analysis review was conducted. This review identified where interactions between subsystems could occur, where common outside factors could influence subsystem states, or where common and recurring events could occur in more than one subsystem. These factors pointed to functions which the integrating controller would need to perform if Space Station autonomy is to be implemented.

For those integrating controller functions which are new or changed from those described in the previous study phase, logic/functional diagrams were prepared to describe the functions.

A step-by-step analysis has been conducted to describe the processes needed to implement each controller element. The implementation description covers software as well as hardware for controller processing. The emphasis in this sub-task was on implementations for use on an early Space Station with some recognition of the need for evolutionary growth planning.

A functional specifications listing was prepared to define preliminary requirements, based on the logic and functional diagrams and the implementation descriptions developed in the previous sub-tasks. These requirements covered functions, inputs, outputs, software features, and hardware characteristics of an overall controller for an early Space Station system.

An assessment was made of specific needs for technology based on all of the descriptive information provided by the functional diagrams, implementation definitions and the functional requirements. Once technology candidates had been identified, trades were conducted to compare benefits in system performance and life cycle cost savings with developmental cost expenditures.

Using the results of the trades, the candidates were ranked according to each of the following categories: (1) schedule pressure, (2) general usefulness of the technology and (3) benefits/cost ratio. These rankings were combined to give an overall prioritization of the candidates which provided a focusing in order to clarify the technology advancement needs, but was not intended to eliminate any candidate.

The results of this prioritization were used to determine those technology areas requiring advancement planning.

2.2.2 Technical Discussion

The subsystem descriptions for the five subsystems considered for autonomous functional control were obtained by interviewing the appropriate Space Station and engineering technology subsystem engineers to obtain diagrams and definitions for each of the subsystems. The descriptions needed to support an analysis of autonomous functional control were not for the internal operations of the subsystem but rather were for the states that subsystem would assume as they performed their functions.

Figure 2.2-1 illustrates a typical space station guidance, navigation and control subsystem. In this figure the primary functions are on the left, simple flow diagrams are in the middle and typical displays to the crew and controls interactions are on the right. This figure shows that there are many modes of guidance and control operation and that significant state control is needed.

The electrical power subsystem consists of elements for power generation, power transmission, energy storage, power distribution, and power conditioning. Figure 2.2-2 shows a typical electrical power subsystem (EPS) configuration for the Space Station. On the left the figure shows an overall Space Station distribution of EPS elements and on the right EPS elements within a single module of the Space Station are shown. Table 2.2-1 lists factors which require integrating control in order to provide autonomous operation of the power generation elements.

The communication subsystem for the Space Station will function through many different links. Automation of the controller for the communications subsystem must consider elements of network control, subsystem element reconfiguration and mode control and command processing control. Figure 2.2-3 shows elements of a typical communications subsystem controller.

The control of a typical local area network data management subsystem (DMS) is accomplished by control software called the network operating system which is resident in the DMS processors. Figure 2.2-4 shows interfaces considered by a network operating system. Because the integrating controllers at the module and Space Station level as well as the subsystem controllers are likely to be embedded in the DMS processors, it is

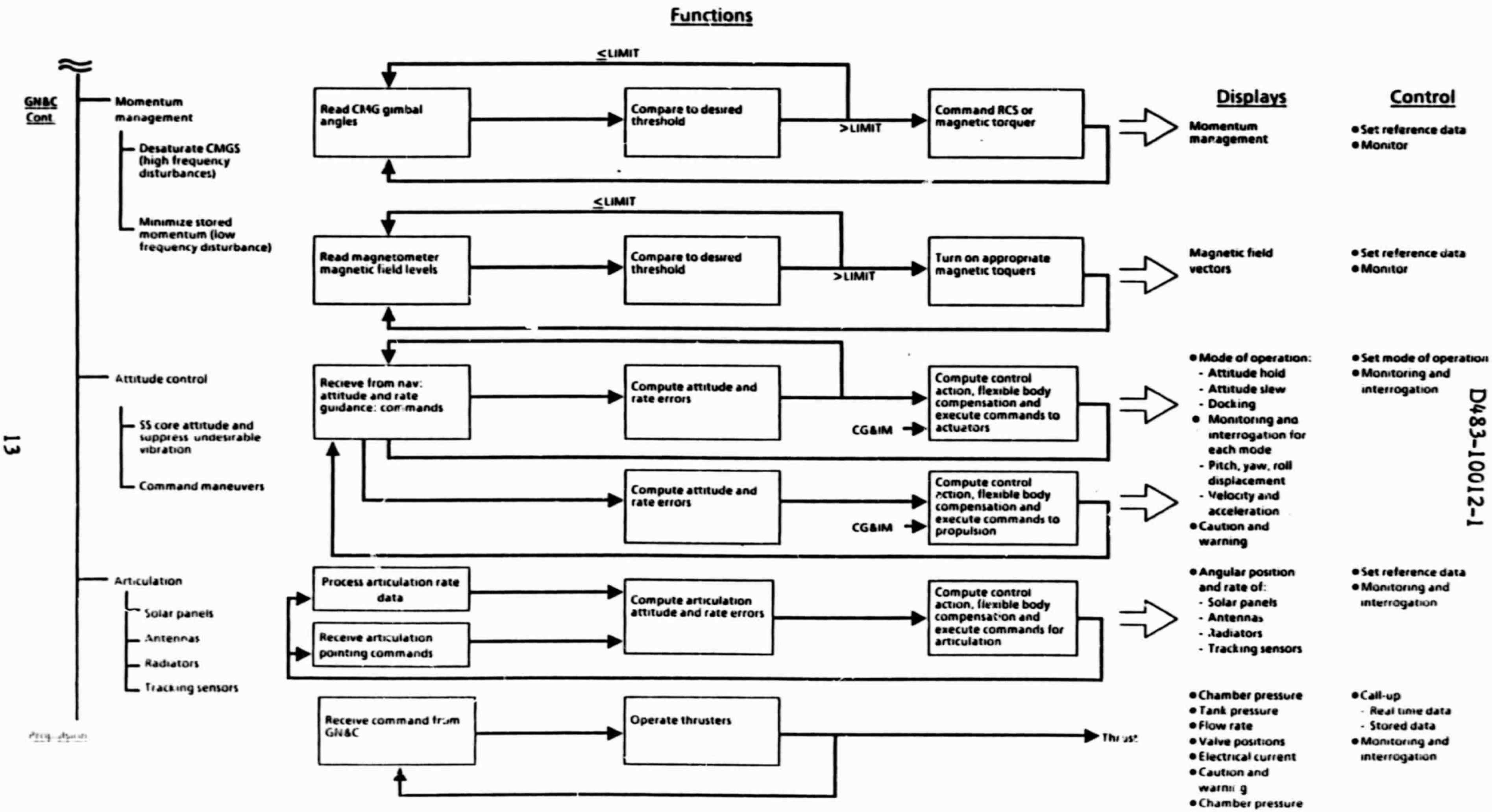

Figure 2.2-1. Typical Guidance, Navigation and Control

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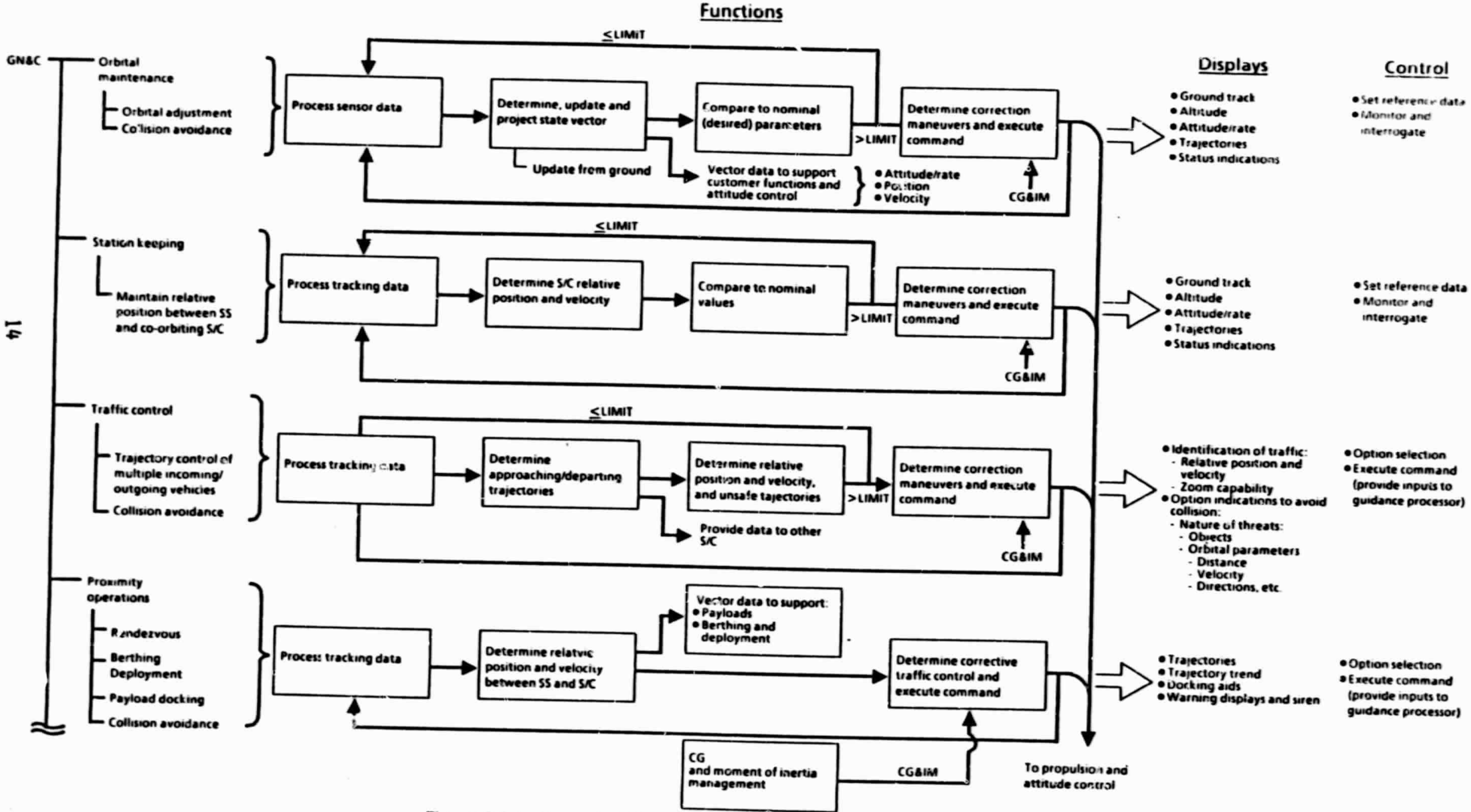

Figure 2.2-1. Typical Guidance, Navigation and Control (Continued)

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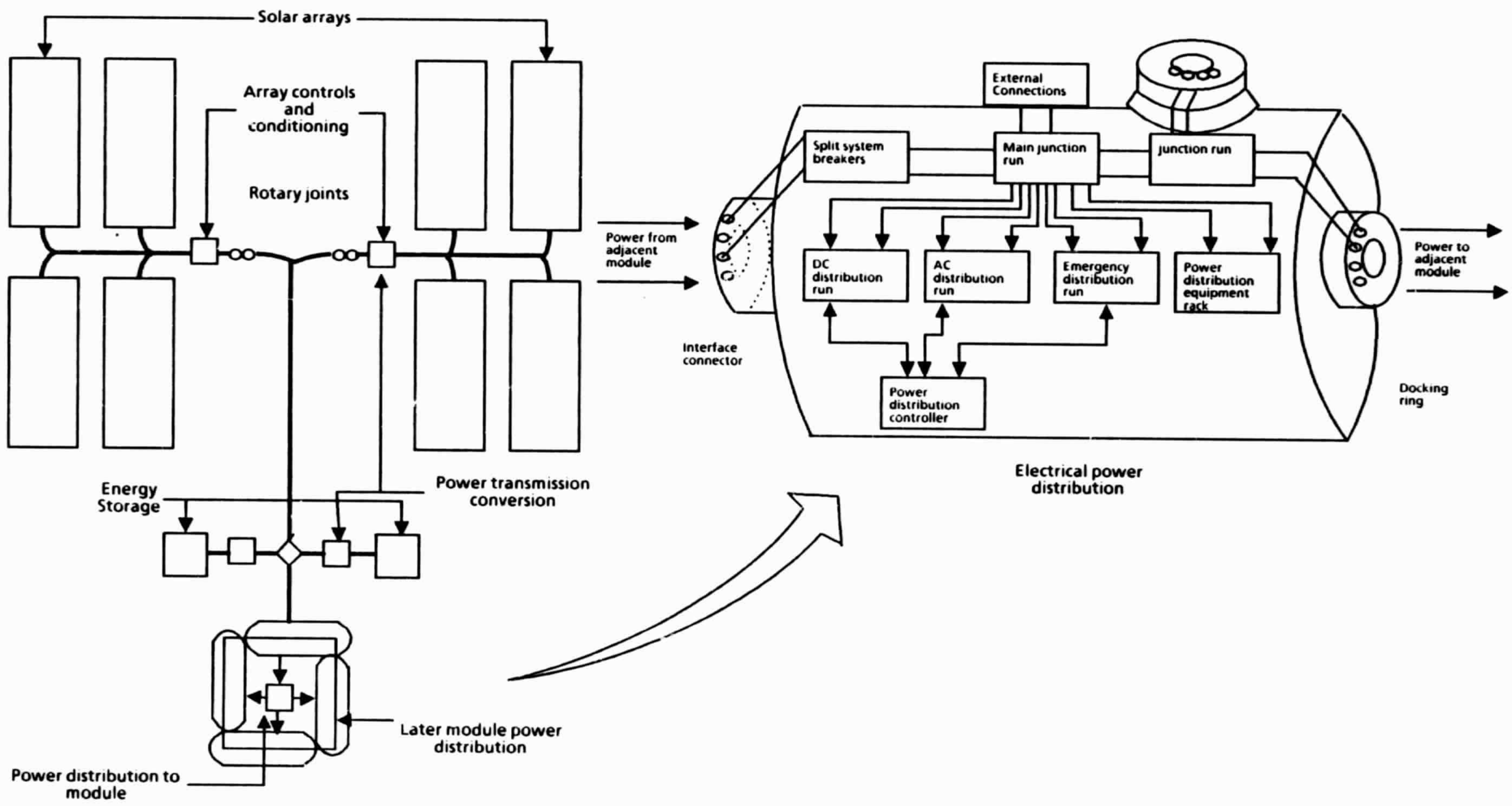

Figure 2.2-2. Typical Space Station EPS Configuration

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Table 2.2-1. Power Generation Autonomy Factors

• Diurnal occultation entry and emergence • Fault detection, isolation, reconfiguration • Energy balance management as a function of degradation	• Trend analysis of cyclic output versus load scheduling • Projection of array performance for maintenance scheduling • Optimize power generation based upon trend data

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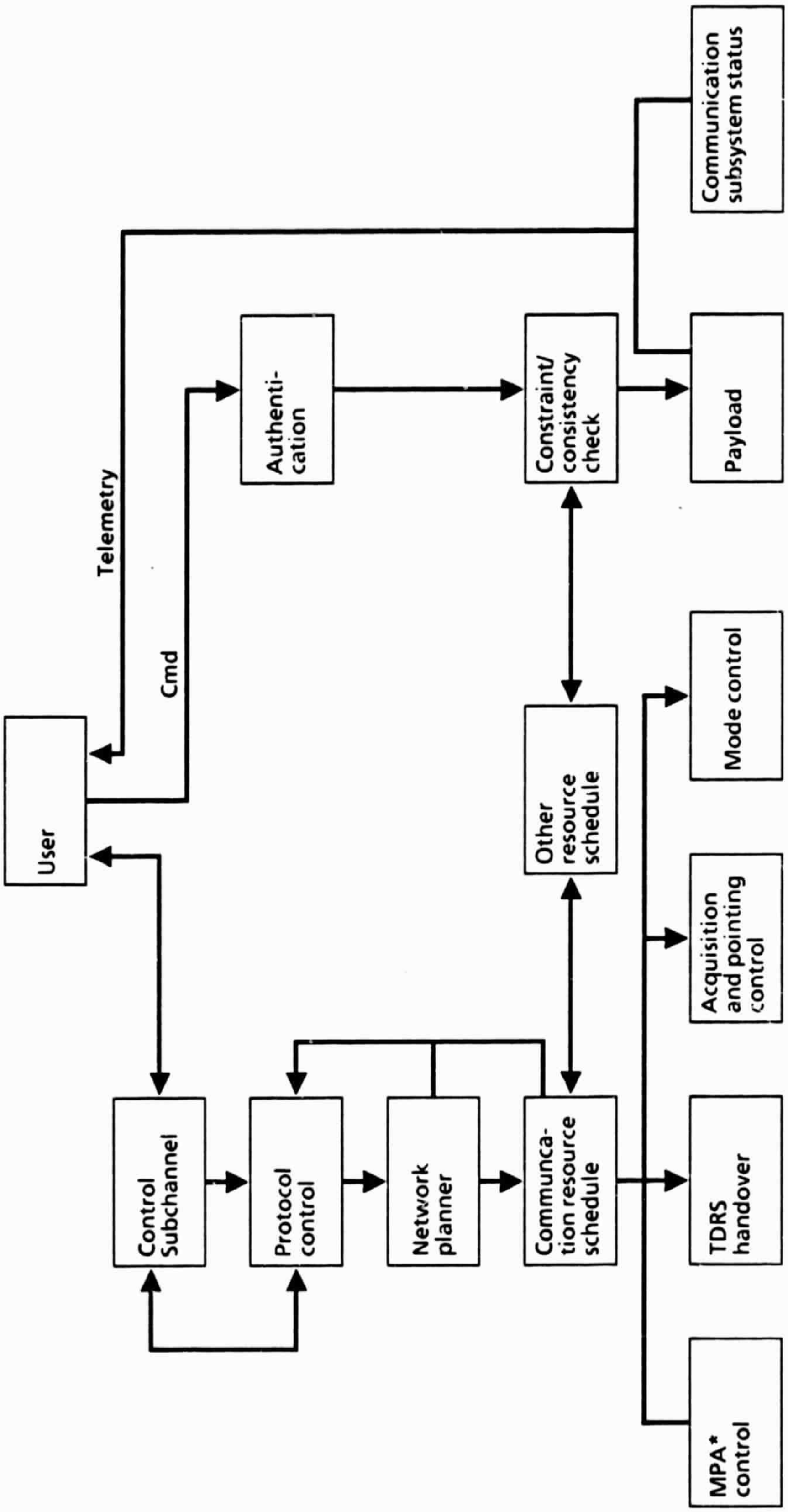

* Multi-beam phased array

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Figure 2.2-3. Typical Communications Subsystem Controller

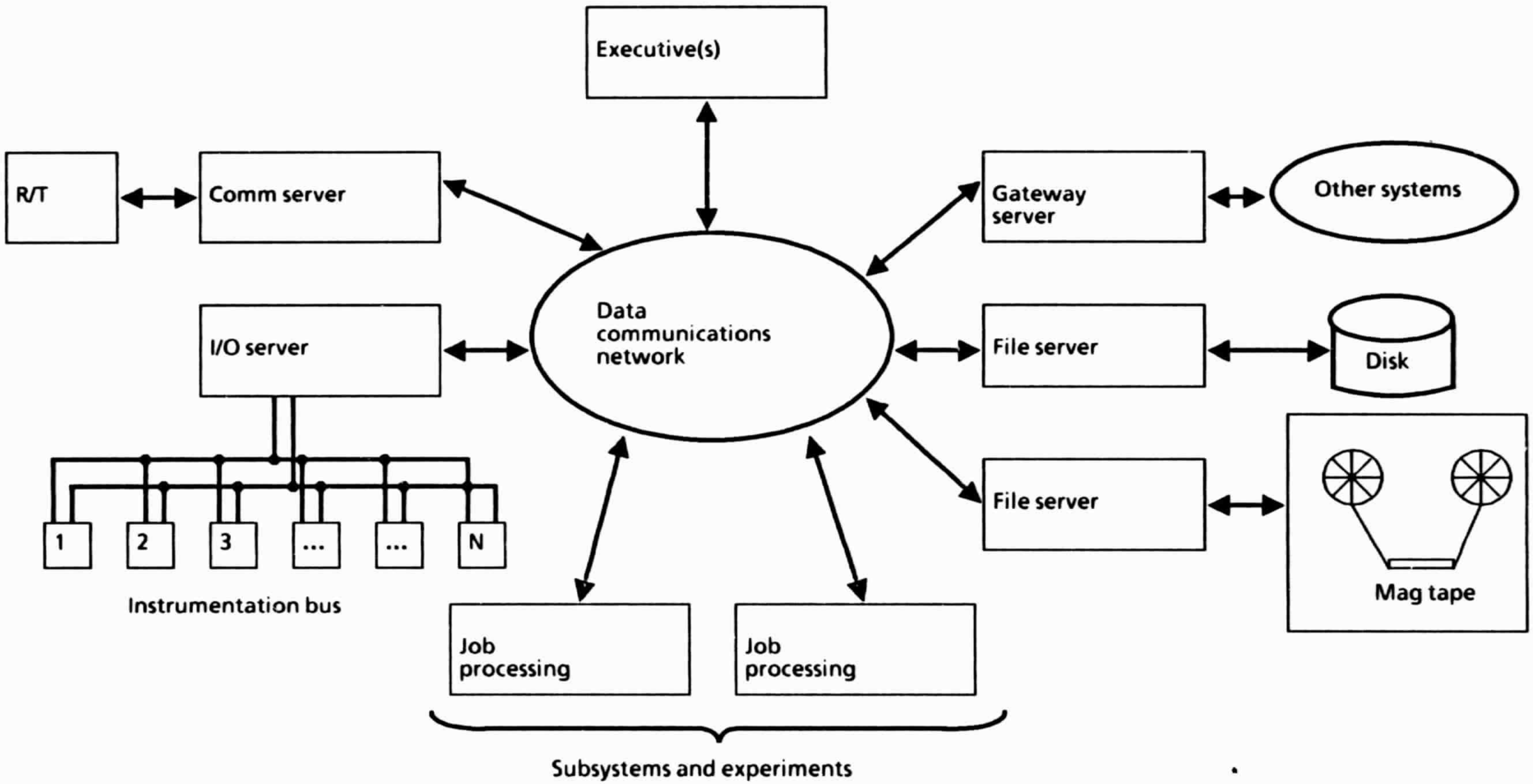


Figure 2.2-4. Typical Data Management Subsystem Network Operating System

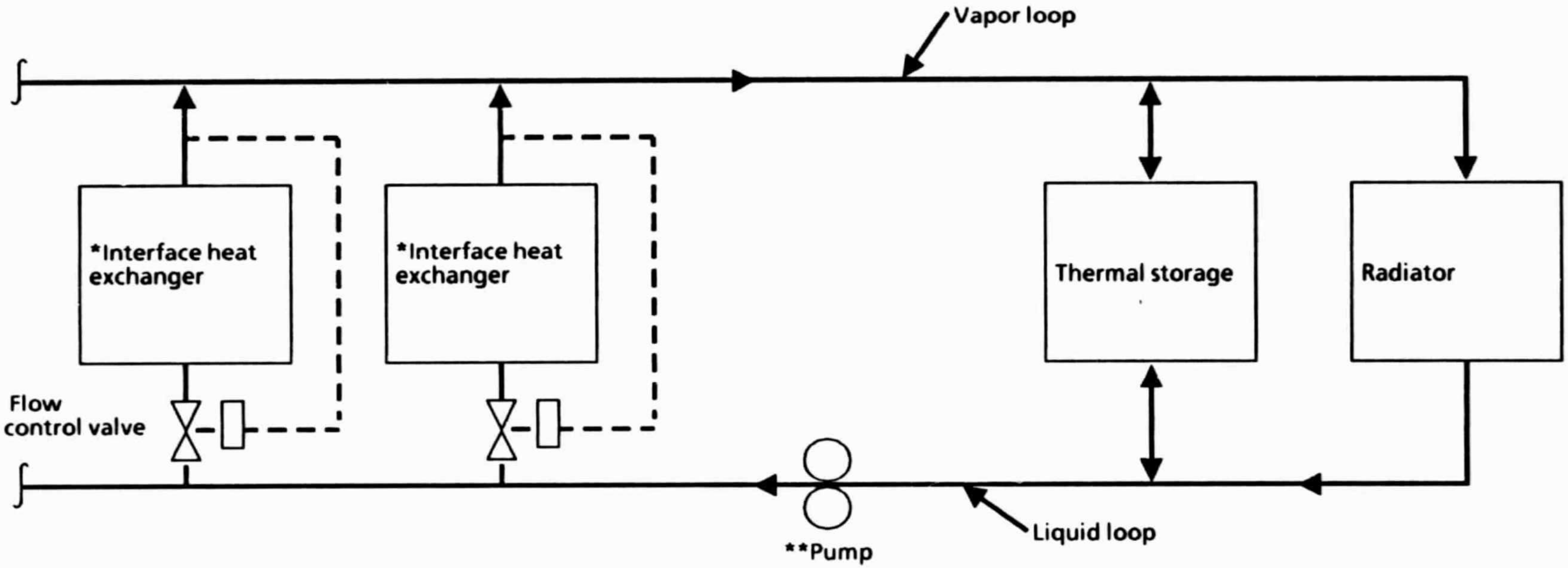
049L-018

easy to overlook the need for DMS control to be considered as a subsystem management function. The modes, reconfiguration, and scheduling for the DMS will need to be integrated just as they are for other subsystems.

The last subsystem considered in this study is the thermal control subsystem. Figure 2.2-5 shows a flow diagram for a typical thermal control subsystem element in the Space Station. The management of the configuration of the elements of a thermal control subsystem distributed on the Space Station would be part of the function of any integrating controller.

Before an analysis of subsystem functions for automation can be conducted, the candidate architecture for integrating control must be described. Figure 2.2-6 shows a typical controller architecture for the Space Station indicating subsystem controllers, module integrating controllers and Space Station level integrating control. For reasons of reliability, commonality, system evolution and conservation of data flow a distributed architecture philosophy for Space Station data management should be adopted. The use of integrating controllers at the module and Space Station level indicate that there will be some centralization of control functions within data management. It is, of course, possible to distribute those controller functions physically over different processors or with redundant processors while a centralized functional aspect is retained. The principle function of the integrating controller is to handle the common operations which occur at the interfaces between the subsystems of the space station. Because the integration of control for subsystem management is hierarchal, the operational functions of each subsystem which were common to one another were considered. Tables 2.2-2, 2.2-3, and 2.2-4 list typical subsystem modes, subsystem reconfigurations, and subsystem state change factors respectively for the five subsystems considered. To integrate the operation of these subsystems with the overall operations and missions of the Space Station, the integrating controller will need to orchestrate these modes, reconfigurations and subsystem states.

Because there is a large volume of data associated with the subsystem management and automation and robotics support functions of an integrating controller, the overall system must be designed to minimize the flow of information between the elements. For that reason the concept discussed here operates on a management by exception. This means that each subsystem controller will manage its own affairs so long as everything is normal and going according to plan. When a subsystem controller detects a change such as a failure condition, the integrating controller will be advised. The overall situation is



* Docked modules, cold plates, etc.

** Baseline uses mechanical pump in liquid loop
Alternatives include

Pump in vapor loop
Osmotic pump system
Ion drag pump system

Figure 2.2-5. Typical Pumped Two Phase Heat Transport System

049L-019

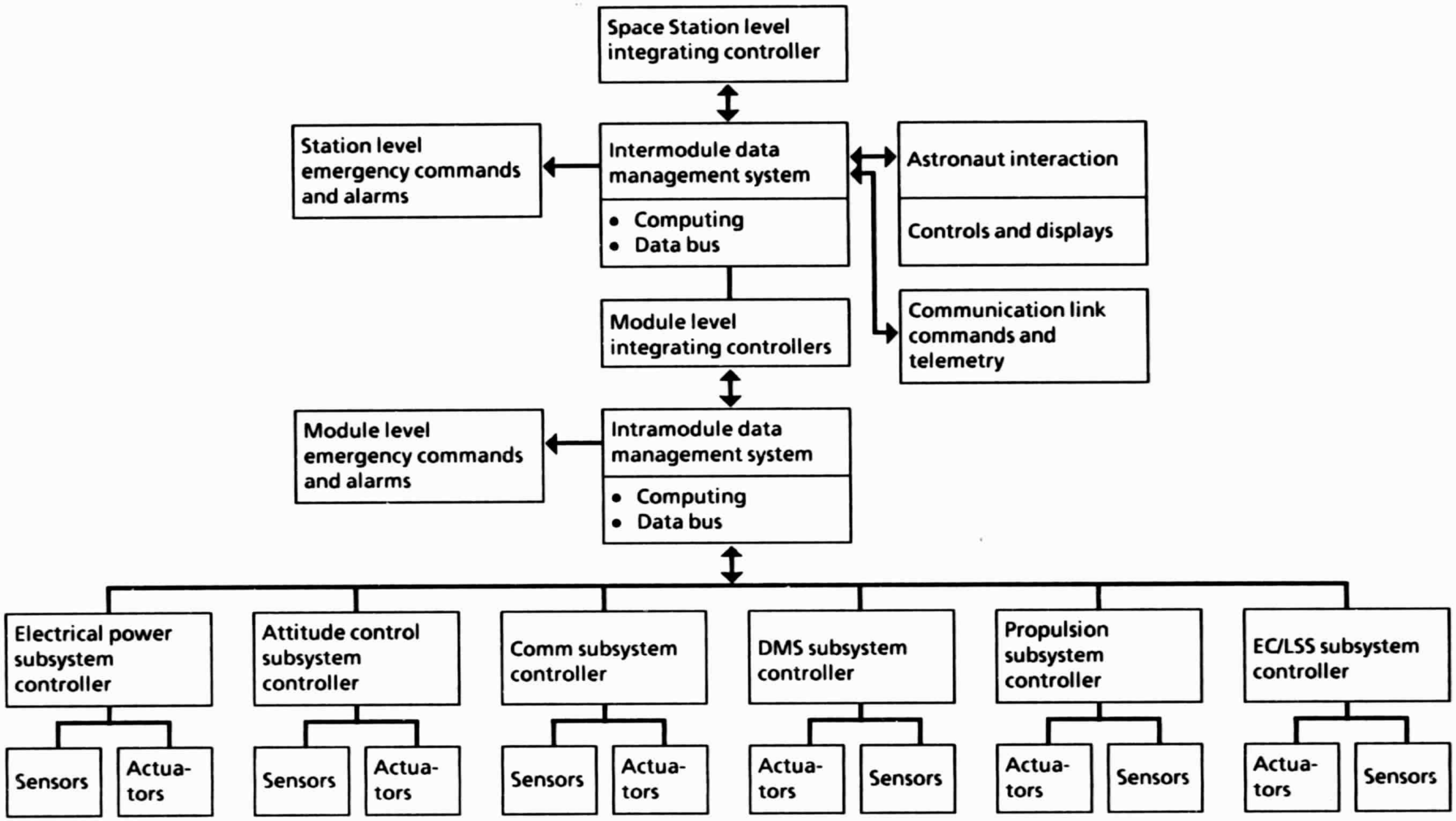


Figure 2.2-6. Architecture for Subsystem Management

049L-020

TABLE 2.2-2 SUBSYSTEM MODES

GUIDANCE, NAVIGATION AND CONTROL

- o Attitude hold
- o Attitude slew
- o Attitude control with orbiter docked
- o GMG wheel desaturation
- o TVC for orbit trim thrusting
- o Acquisition and start up
- o Off
- o Reconfiguration

ELECTRICAL POWER

- o Sunlight normal
- o Darkside normal
- o Battery reconditioning
- o Solar array degradation
- o Reconfiguration
- o Off

COMMUNICATIONS

- o Direct with other spacecraft
- o With other spacecraft via TDRSS
- o Tracking
- o Downlink via TDRSS
- o Downlink via GSTDN
- o Downlink to user ground station
- o Unencrypted (not IOC)
- o Reconfiguration
- o Off

DATA MANAGEMENT

- o Normal (full service)
- o Reduced service
- o Data dumping to archieval memory
- o Reconfiguration
- o Off

THERMAL MANAGEMENT

- o Normal
- o Reduced
- o Reconfiguration
- o Off

TABLE 2.2-3 SUBSYSTEM RECONFIGURATIONS

GUIDANCE, NAVIGATION AND CONTROL

- Thrusters in use
- Allocation of control signal to controllers
- Redundant paths
- Alternate paths
- Sensors in use

ELECTRICAL POWER

- Batteries in use
- Solar array sections in use
- Redundant paths
- Alternate paths
- Power busses in use

COMMUNICATIONS

- Antennas in use
- Redundant paths
- Alternate paths

DATA MANAGEMENT

- Gateway devices engaged
- Redundant paths
- Alternate paths

THERMAL MANAGEMENT

- Radiators in use
- Thermal busses in use
- Pumps in use
- Heat exchanger in use
- Redundant paths
- Alternate paths

TABLE 2.2-4 SUBSYSTEM STATE CHANGE FACTORS

GUIDANCE, NAVIGATION AND CONTROL

- o Slew rate
- o Dead band size
- o Identification of principle axes
- o System gains
- o Wheel desaturations interval
- o Wheel desaturation rate
- o Wheel desaturation controller gains
- o Storage of RCS propellant
- o Maintenance schedule
- o Failure modes/anomalies

ELECTRICAL POWER

- o Load management
- o Power source management
- o Energy balance
- o Management of excessive power
- o Light/darkside passage
- o Maintenance schedule
- o Failure mode anomalies

COMMUNICATIONS

- o Frequencies (S-band or Ku-band)
- o Data rates
- o TDRS in use when more than one available
- o Maintenance schedule
- o Failure modes/anomalies

DATA MANAGEMENT

- o Data rates
- o Computer op rates
- o Data stored
- o Maintenance schedule
- o Failure modes/anomalies

THERMAL MANAGEMENT

- o Temperatures
- o ΔT's
- o Light/darkside passage
- o Maintenance schedule
- o Failure mode/anomalies

then examined by the integrating controller so that directions are given back to the subsystems. Figure 2.2-7 illustrates an example of the automated decision making process using attitude control as an example subsystem. The subsystem controller in this example checks its status every few milliseconds. As long as the status is okay no integrating controller action is requested. When the status is not okay, the subsystem controller performs its internal diagnostics and informs the integrating controller. In this example the attitude control subsystem controller detects a failure in LR-22 and assesses the consequences of a switch to the redundant element as a transient in pitch, yaw and roll attitude. The integrating controller checks the status of Space Station subsystems and mission operations. Then, it determines that experiment #16 cannot tolerate the predicted attitude transient. The integrating controller therefore directs the attitude control subsystem controller not to switch to the redundant element.

This example indicates one type of decision making to be performed by an integrating controller. Another type is rescheduling decisions for operations on the Space Station resulting from unforeseen events. Again the integrating controller will be informed (usually by astronaut inputs) and the information results in a need to change directions issued to subsystem controllers. The following is a list of typical status elements that the integrating controller will direct a subsystem controller to change.

- Prioritization lists
- Scheduling
- Operating constraints
- Override commands for emergency conditions.

These directions for change would affect mode and state control of the individual subsystems in response to anomalies or unscheduled events.

Figure 2.2-8 gives a flow diagram to describe at a top level those steps to perform integrating controller functions.

1. Information is collected by the integrating controller from the astronauts via control and display units, from the subsystem controllers via the data management system, and from the ground via the telecommunications system (IOC especially but less of this as Space Station autonomy is developed). This information will indicate state changes, reconfigurations, schedule changes, environment changes, and anomolies which effect the operation of the Space Station.

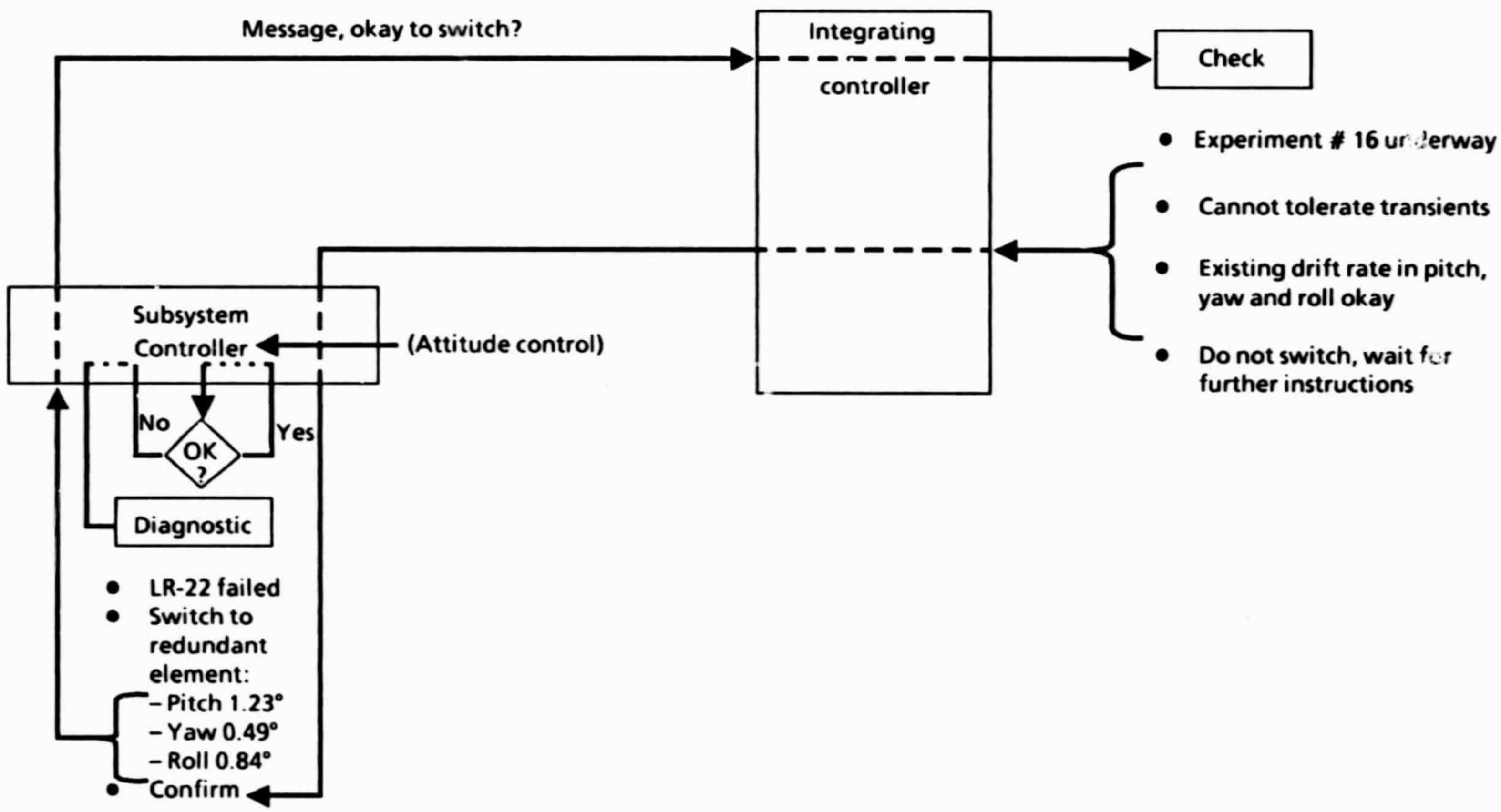


Figure 2.2-7. The Automated Decision Makers

049L-021

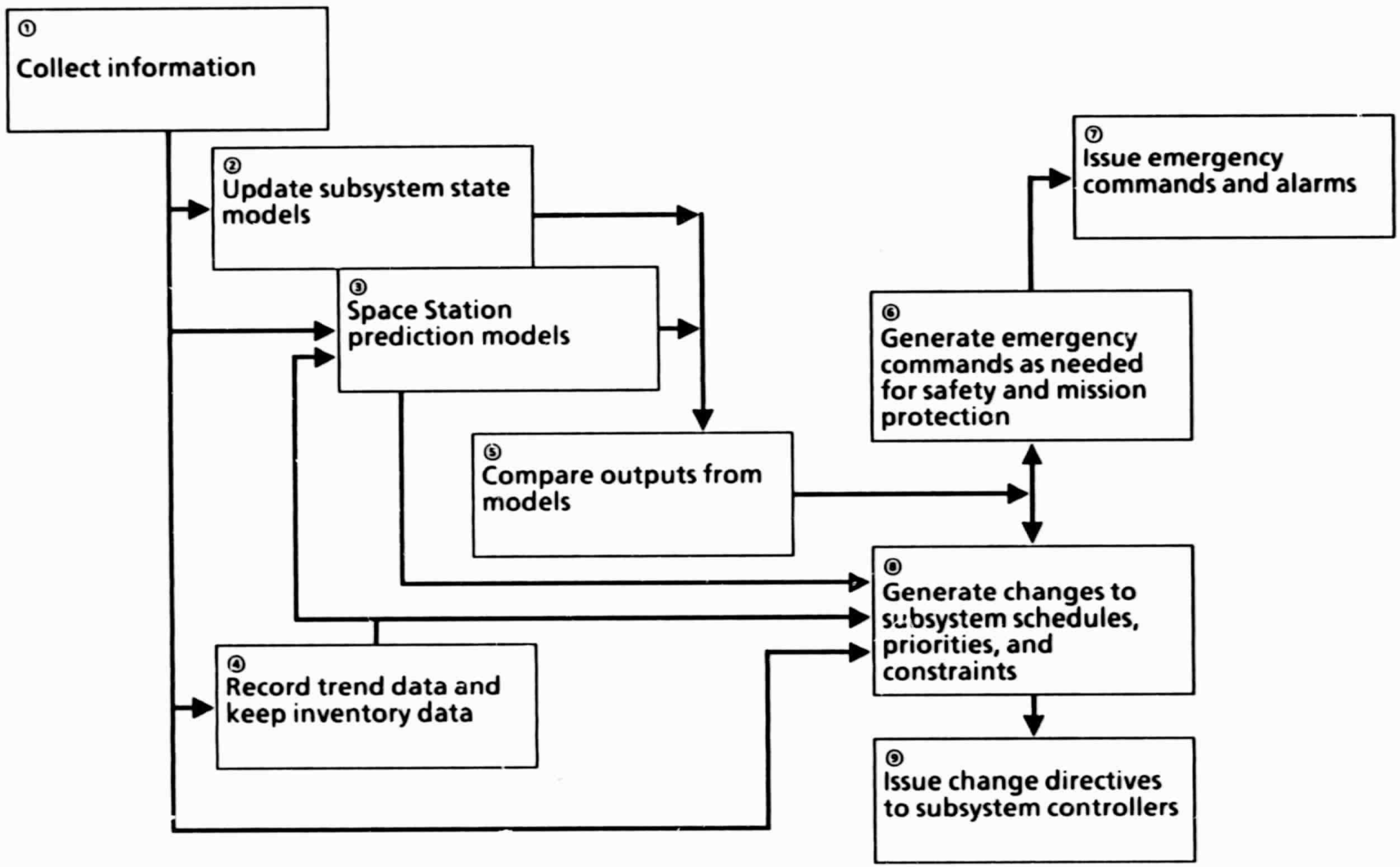


Figure 2.2-8. Flow Chart for Integrating Controller Functions

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2. A state and mode simulation will be run for all Space Station subsystems. This will produce a description of the mode, configuration and output performance parameters of all of the subsystems resulting from the passage of time as the simulation is periodically updated based on the collected information.

3. Separate state simulations will be run faster than real time to predict the consequences of letting the current situation continue, or to simulate the results of hypothetical inputs to subsystem controllers in response to anomalous conditions.

4. Trend data and other historical data are updated to reflect the latest collected information.

5. An assessment is made for each subsystem interface based on current state outputs from the mode simulation and from the the predicted consequences which would occur by letting the current situation continue. Unsatisfactory situations are identified by the integrating controller and assessed (probably an E.S. application) to be either life or mission threatening indicating an emergency condition or non-threatening indicating an anomalous condition.

6. When an emergency condition exists, the integrating controller will generate emergency commands to be issued to the subsystem controllers. These commands will be designed to place the station in a condition which will support the life of the crew and sustain the mission in accordance with predetermined priorities. Another part of the emergency command process will be the activation of alarms and emergency (explain type) information displays to the crew and transmissions of data to earth.

7. The integrating controller will issue the emergency commands to the appropriate subsystems and alarms and will determine the schedule and sequence for removing those commands either with a continuation of the emergency state or after collected information shows a return to normal.

8. For those conditions which are judged to be anomalous, but not life or mission threatening subsystem change directives are needed. For these, the integrating controller will determine (again E.S. technology may be needed) a workable compromise using the various predictions from the hypothetical simulations as well as trend data and direct input data. Once a workable compromise has been

selected, the integrating controller will generate change directives to be issued to subsystem controllers.

9. This is similar to step 7 in that appropriate subsystems will be directed and the schedule for retaining those directives will be determined.

The key components of the integrating controller are the simulation modules and the expert systems. Most of the feasibility assessment depends on the feasibility of developing and implementing these items. Some of the factors to be considered are:

Can the modules be developed?

Validity and verification of the models

Speed of the models

Cost to develop the models

The state change rate is expected to be low relative to the processing speed so several software modules can be executed in series in a single processor, but more than one processor will probably be needed for all of them. The same is also true of the expert systems. They may require separate processors, but may also be executed on the same processor if the time is available.

The impact of the integrating controller on the data management subsystem depends on the program size and processing throughput required for the various program modules. Quantitative estimates cannot be made without further specification of the data management subsystem computers and additional characterization of the integrating controller functions. Some qualitative estimates however can be made and are summarized in Table 2.2-5. Size refers to the amount of memory required for the program modules and their data. Those indicated as large are the simulations models and the expert systems. These are expected to require on the order of half of the memory of a DMS processor. The subsystem models may require much more since they are multiple models. The timing column indicates demand for processor throughput (operation per second). This is given in two parts, frequency and loading. The frequency indicates how often the module needs to be executed. As shown, all are required continually except the Emergency Handler and Change Handler which are required in response to changes in conditions. The loading refers to how much of the processor's throughput is required.

Another important factor in implementing the integrating controller on the data management subsystem is the data flow required. Table 2.2-6 indicates, for the major

Table 2.2-5. Integrating Controller Software Sizing and Timing

Module	Size	Timing (Frequency/Loading)
I/O handler	Small	Continuous/Moderate
Subsystems models	Large	Continuous/High
Space Station prediction models	Large	Continuous/High
Change monitor	Large	Continuous/Moderate
Emergency handler	Small	Infrequent/Low
Change handler	Large	Occasional/Moderate
Recording and trendiing	Large	Continuous/Moderate

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Table 2.2-6. Integrating Controller Data Flow

From/to	Type of Data	Frequency	Amount
From Subsystems	Operational Data	High	Large
	State Changes	Moderate	Small
	Mode Changes	Low	Small
	Anomalies/Failure Data	Low	Small
	Reconfigurations	Low	Small
	Environmental Changes	Low	Small
From Ground and Astronauts to Subsystems	Schedule Changes	Low	Small
	Prioritization Changes	Low	Small
	Schedule Changes	Low	Small
	Prioritization Changes	Low	Small
	Changes to Constraints	Low	Small
	Override Commands	Low	Small

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sources of data flow, the frequency and amount of data flow from the subsystems, from external sources and to the subsystems. The only data item likely to place demands on the data management subsystem data buses is operational data. Care must be taken in the development of the integrating controller in selection of the operational data items needed for integrating controller operation.

The key to developing the integrating controller is the ability to develop effective models of the subsystems of the Space Station and effective decision making expert systems. For the models, this involves selection of an adequate model development language, proper assessment of the accuracy of the models and methods to translate the models into software suitable for real-time control. Without building any models this is about a 3 to 6 man-month effort. To develop an experimental model of a Space Station subsystem and convert for real time use is a 1 to 2 man-year effort. The number of subsystems multiplied by 2 man-years each gives an indication of the scope of effort to develop subsystem models. The prediction modelling effort would be at least as much as the subsystem modelling but would also involve the use of expert system technology.

Based on experience, the following expert system metrics for an IC are "guestimated." Approximately 1000 to 5000 rules will be required. The computer used should run at about 2 MIPS and have from 1 to 4 megabytes of memory.

Essentially, R1 was developed over a four year period at a rate of about 850 rules per year. There was an expenditure of about 4 man-years of effort per year. Based on these figures and the estimates of the preceding paragraph, an IC will require from 1.25 to 6.25 years to develop and from 5 to 25 man-years of efforts.

The use of expert system development tools is essential if an acceptable level of productivity is to be achieved during the development process. Unfortunately, most existing tools are not suitable for developing expert system for the integrating controllers. They suffer from three general types of deficiencies.

First, existing tools are designed to handle static rather than dynamic situations. An IC, of course, requires the ability to monitor and respond to situations that develop over time.

Second, most tools interface very poorly with existing software or software based on conventional rather than AI principles. A successful IC will require a blend of conventional and AI techniques.

Third, and related to the second deficiency, most existing tools are designed to interface with a human user rather than other systems. Clearly, the latter capability will be required in an IC.

Currently, no AI hardware is available that is suitable for "field" use such as on a space station. This problem may correct itself in the future since TI has announced the development of a compact Lisp machine for the Navy.

The discussion above suggests several technology areas needed for implementation of the integrating controller concept. The following is an unranked listing of those suggested technologies.

- o Developing effective simulation models
- o Adapting expert systems to real time operations
- o Developing expert systems that interface well with conventional software
- o Developing knowledge engineering techniques to cope with emerging technologies
- o Space-qualified compact LISP computer

2.2.3 Technology Candidate Comparisons

The comparisons of the technology areas based on schedule pressure have considered the following: (1) The anticipated duration of the advancement program, (2) contributions from other advancement activities such as the DARPA strategic computing initiative program, and (3) the anticipated need date of the technology.

General usefulness comparisons of the technology areas consist of two parts: (1) usefulness of the technology to the integrating controller and (2) usefulness of the technology to other parts of the Space Station and other parts of the technical community.

The benefits resulting from an on-board integrating controller over the first ten years of Space Station operation were estimated in the previous study phase and no new information has been developed in this phase. The estimate is described in some detail by paragraph 5.3.8 of Boeing document D180-279354-2 but Table 2.2-7 is included here to summarize the benefits estimate metrics.

The advancement costs have been estimated for each technology candidate and are reported in some detail in volumes II and III of this report as well as on Table 2.2-8.

Table 2.2-7. Integrating Controller Benefits Estimate

- Monitoring effort phased out over five years
  - First year full mission control center coverage
  - Second through fifth years—mission controllers reduced by 5
  - After fifth year—mission controller and onboard monitoring reduced to 1/10 time for each
- Labor rate for mission controllers is $1500 per day and astronaut is $77,000 per day
- Efficiency and maintenance cost savings is $2.5M per year
- The integrating controller provides half of total benefits = $54M for ten years.

Table 2.2-8. Technology Advancement Cost Estimates

- Developing effective simulation models
  - 2 man year effort per model X 8 models = 16 man years plus real time simulation development costs = $2.0M
- Adapting expert systems to real time operations
  - Estimate 4 man years to adapt DARPA results to I.C. usage = $480K
- Developing expert systems that interface well with conventional software
  - Estmate DARPA results require a ten man-year effort to adapt software concepts to I.C. use = $1.2M (note: $2.04M effort under technology definition includes effort to integrate software with Space Station processors)
- Developing knowledge engineering techniques to cope with emerging technologies
  - Estimate DARPA results plus 2 man-year effort to adapt to Space Station usage = $240K
- Space qualified compact LISP computer
  - Estimate $4M development and testing effort in addition to DARPA work

The estimates of Table 2.2-7 were partitioned according to the contribution of each of the technology candidates to the overall bendfits provided by the integrating controller. Using these partitioned benefits, the benefits to cost ratios were computed. Volume II of this report gives the partitioning rationale used. The resulting benefits to cost ratios of the five candidates are given as Table 1.1-1 of this volume.

Based on the schedule pressure, general usefulness, and benefits to cost comparisons discussed above, the five technology candidates for autonomous functional control were prioritized as indicated by Table 1.1-2 in the Introduction section of this volume.

2.2.4 Conclusions

The conclusions that can be drawn from this study are that several technology advancements are necessary if an automated integrating controller is to be part of the Space Station system. The urgency of NASA initiatives in each of these areas is tempered somewhat by the DARPA plans for a strategic computing study.

Because the technologies associated with adapting expert systems to real time operations and the advancement of techniques for knowledge engineering are significant parts of the DARPA study, and because those two candidates have limited connection with the unique characteristics of the Space Station, this add-on study has not developed advancement plans for them.

The three advancement candidates that have been considered in the advancement planning for this add-on task will also benefit from the DARPA study. The effect of that benefit will be an improvement in the benefits to cost ratios for the candidates. If the DARPA study proceeds immediately there may also be a schedule benefit for the candidates identified here. It will be necessary for NASA to be in close contact with the DARPA study to insure that the advancements produced are applied to the Space Station in a timely manner. It will also be necessary to adapt the DARPA results for Space Station use and that adaptation will be facilitated by close contact with the development of those results.

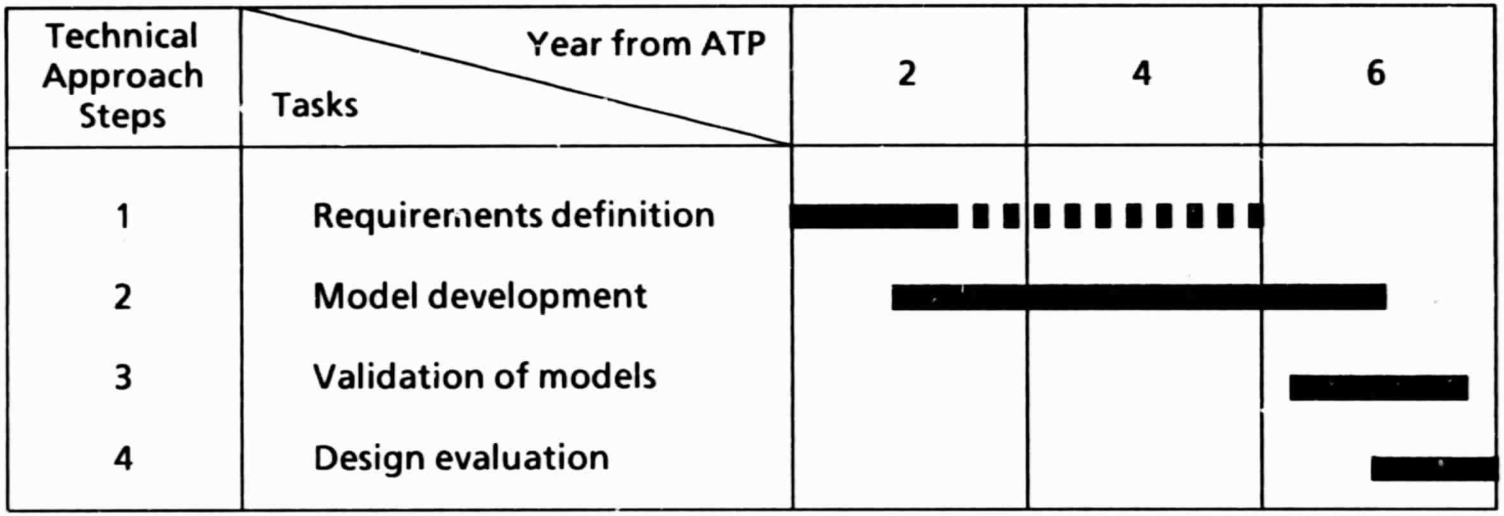
2.2.5 Technology Advancement Plans

Advancement plans for the integrating controller technologies will be developed to cover two phases. Phase I is intended for the IOC Space Station. It will consist of the

development of subsystem models designed to evaluate state and mode conditions of seven prime subsystems and an overall Space Station needs model. These subsystem models will continuously assess the current operating conditions and synthesize the status information needed by the IC. The overall station model will be operating concurrently to define the needs of the Space Station as a whole. The actual functional conditions will be compared with the generated requirements and displayed to the astronauts and ground controllers. Initially, corrective action will be determined and subsystem adjustments made by humans with the IC acting in an advisory capacity.

Phase II will incorporate the overall integration of autonomous functional control. An expert system will be developed to perform the situation comparison task and determine corrective action necessary through the use of encoded knowledge derived from experts in the subsystem fields and the experience of the ground controllers and astronauts involved in Phase I.

Figures 2.2-9 through 2.2-11 and Tables 2.2-9 through 2.2-11 describe plans for the three technology candidates which are not considered to be adequately covered by the DARPA Strategic Computing Study: (1) effective Space Station software simulation models, (2) expert system/conventional microprocessor interfaces, and (3) inference processors for spacecraft applications. The plans are presented as stand alone programs. However, in the case of the software interface development, the inference processor is the heart of the expert system which is one side of the interface, and therefore must be available in order to design and build the software. In the case of the Space Station and subsystem simulation development, the models produced by the technology program will be much more useful if produced using hardware and software techniques resulting from the real-time expert system and the inference processor programs. Initial model development using conventional techniques should be acceptable, though.



Dark lines indicate heavy emphasis.

Dotted lines indicate coordination emphasis.

Figure 2.2-9. Schedule for Space Station Subsystem Simulation Development Plan

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Table 2.2-9. Resources for Space Station Subsystem Simulation Development Plan

Technical Approach Steps	Tasks \ Year from ATP	2	4	6	Total
1	Requirements definition	260	100		360
2	Model development	300	800	50	1150
3	Validation of models		220	150	370
4	Design evaluation			120	120
Total		560	1120	320	2000

1) Figures in $1000 (1984)

2) Estimates taken from midterm report, "Space Station Systems Technology Study"

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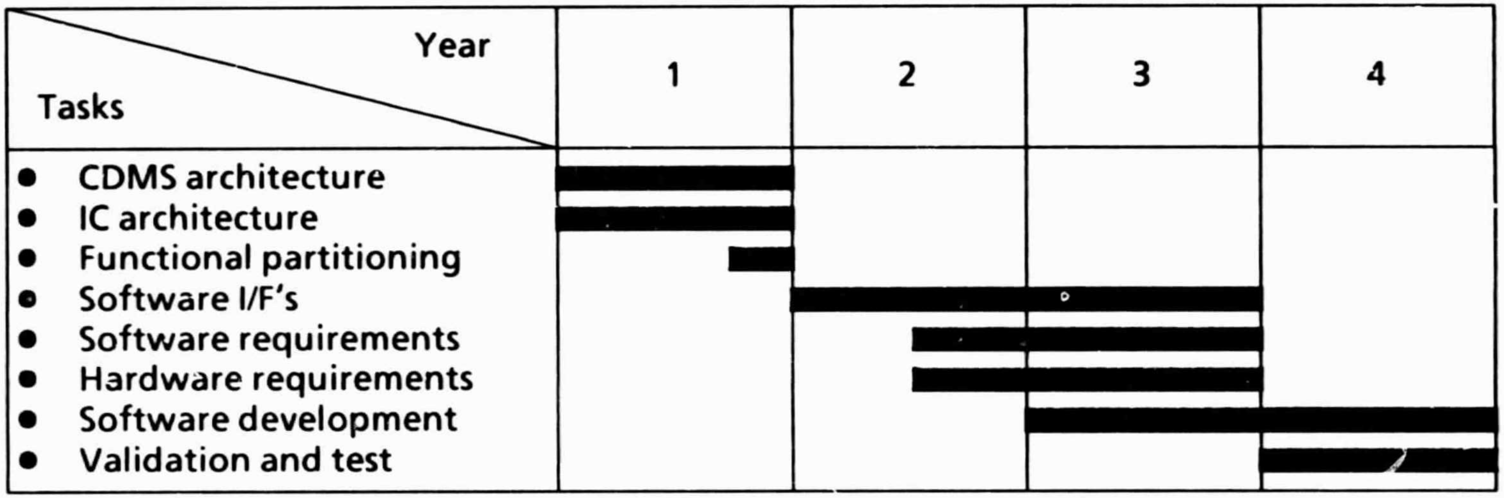

Figure 2.2-10 Schedule for IC Expert System/Conventional Microprocessor Software Interfaces

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Table 2.2-10. Resource Requirements for IC Expert System/Conventional Microprocessor Software Interfaces

Step	Tasks \ Year from ATP	1	2	3	4	Total
1	CDMS architecture	60				60
2	IC architecture	60				60
3	Functional partitioning	120				120
4	Software I/F's		300	60		360
5	Software requirements		150	90		240
6	Hardware requirements		150	90		240
7	Software development			360	120	480
8	Validation and test				480	480
Total		240	600	600	600	2040

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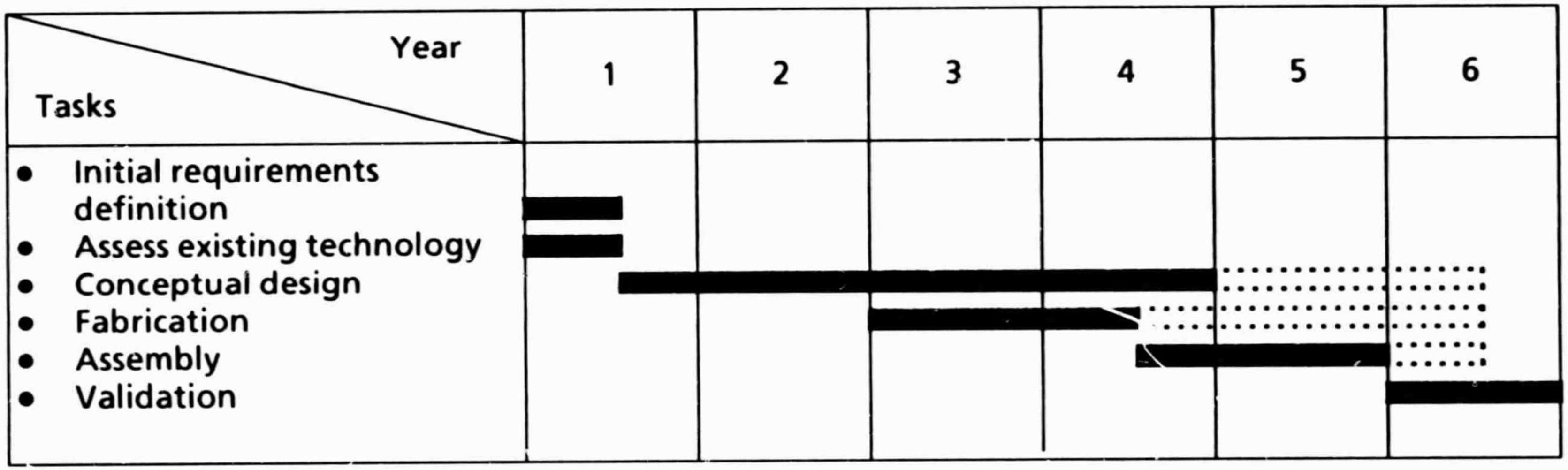

Figure 2.2-11. Schedule for Development of Compact Lightweight Inference Processor for Space Applications

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Table 2.2-11. Resource Requirements for Development of Compact Lightweight Inference Processor for Space Applications

Step \ Year	1	2	3	4	5	6	Total
Initial requirements definition	150						150
Assess existing technology	150						150
Conceptual design	300	600	200	100			1200
Fabrication			440	440			880
Assembly				100	620		720
Validation						600	600
Total	600	600	640	640	620	600	3700

049L-006

2.3 ATTITUDE CONTROL IMPACT FROM STRUCTURAL DYNAMIC MOTIONS

The objective of the previous study phase was to initiate the identification of technologies required for the solution of the control-structure interaction problem in Space Station design. The approach was to determine through analysis and simulation the degree to which conventional controller technology is applicable to attitude regulation of a Space Station with large flexible solar arrays.

The objective of the current phase of the study will be to extend the efforts of the previous study to include symmetric mode analysis, elemental structure damping, active controller evaluation and incorporation of stiffer structure in the solar array design. Accordingly, a detailed evaluation of Space Station control and dynamic performance in the presence of structural interaction excited by orbiter berthing operations and crew activity was performed. Control requirements for the symmetric modes were derived and motion of the flexible appendages was studied in detail. The uncontrollable modes identified in the previous study phase were controlled by selected techniques including passive and active stabilization. Passive stabilization of solar array torsional vibration focused on the design of discrete viscous damping mechanisms in the astromast structure. Active torsional vibration suppression considered the use of the beta tilt and sun tracking actuators. Vibrations to the existing structural configuration considered alternate solar array deployment schemes which offer substantially stiffer structures in torsion.

The previous phase of the study considered only the anti-symmetric modes of vibration. This was justified under the assumption that the disturbances were manifest as pure couples. This assumption is not valid since the most frequent source of disturbance is derived from crew activity which imparts both force and torque to the vehicle. Figure 2.3-1 defines symmetric and antisymmetric bending modes. The sketch depicts typical normal mode shapes for a simple structure where the mass of the solar arrays are concentrated at the tip of the boom. Symmetric and antisymmetric bending is excited by forces and torques respectively as shown. The actual motion of a multiply connected set of flexible appendages is of both types of bending.

2.3.1 Approach

The structural model developed in the previous phase of study will be reviewed here. This brief discussion will help to establish a reference for subsequent discussions.

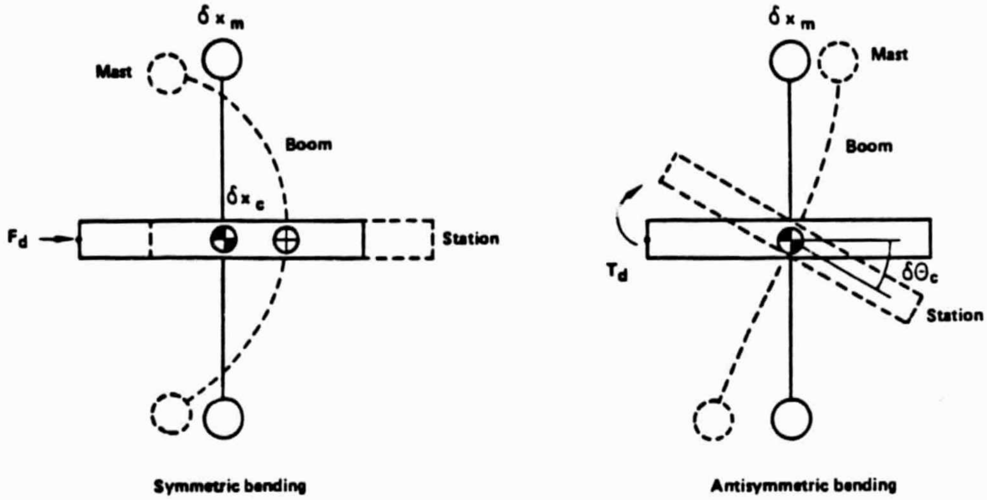


Figure 2.3-1. Definition of Symmetric/Anti-symmetric Bending

A pictorial view of the study configuration is shown in Figure 2.3-2. This configuration represents the all-up fully evolved configuration with SEPS type solar panels partially deployed. Four simulation tasks in this study were performed with the structural configuration using SEPS type solar arrays indicated above. The fifth task requires modification of the current configuration to include arrays with improved structural properties.

The previous study formulation of the model for the crew activity forcing function assumed a pure torque couple about the center of mass with no resultant translational forces through the center of mass. This study can apply both forces and torques at any desired point of application on the structure and use the resultant state vector (rotational plus translational states) and accelerations to establish control requirements as a function of acceptable levels of acceleration.

The uncontrolled vibration in the solar array structure is damped by introducing discrete passive torsional control elements at either ends of the mast. Designs for both tip and root mounted dampers are presented and feasibility for space application is discussed.

Active stability augmentation when applied to a large structure like the Space Station should incorporate both aspects of performance and vibration suppression. The control objective for performance would be to shape the closed loop response such that motions of core and solar arrays are decoupled. This would imply for example, that disturbances due to crew activity would impart motion to the core but would tend to keep the solar panels fixed with respect to the sun. The actuator package includes a three axis linear core mounted torquer, solar array sun tracking and beta tilt actuators. The sensors include a core mounted rotational sensor package, and rotational motion measurements at critical locations on the flexible elements. The preliminary design of an active vibration suppression is presented where collocation of sensors and actuators is not a constraint.

A symmetric mode vibration suppression system using a low thrust reaction jet control system has been simulated a part of this study. The control objective was to null translational rates of the boom and mast relative to the core using resisto jet controllers mounted on the solar panel booms. This mode of control was investigated as an alternative to redesign of the boom and mast servoactuator system.

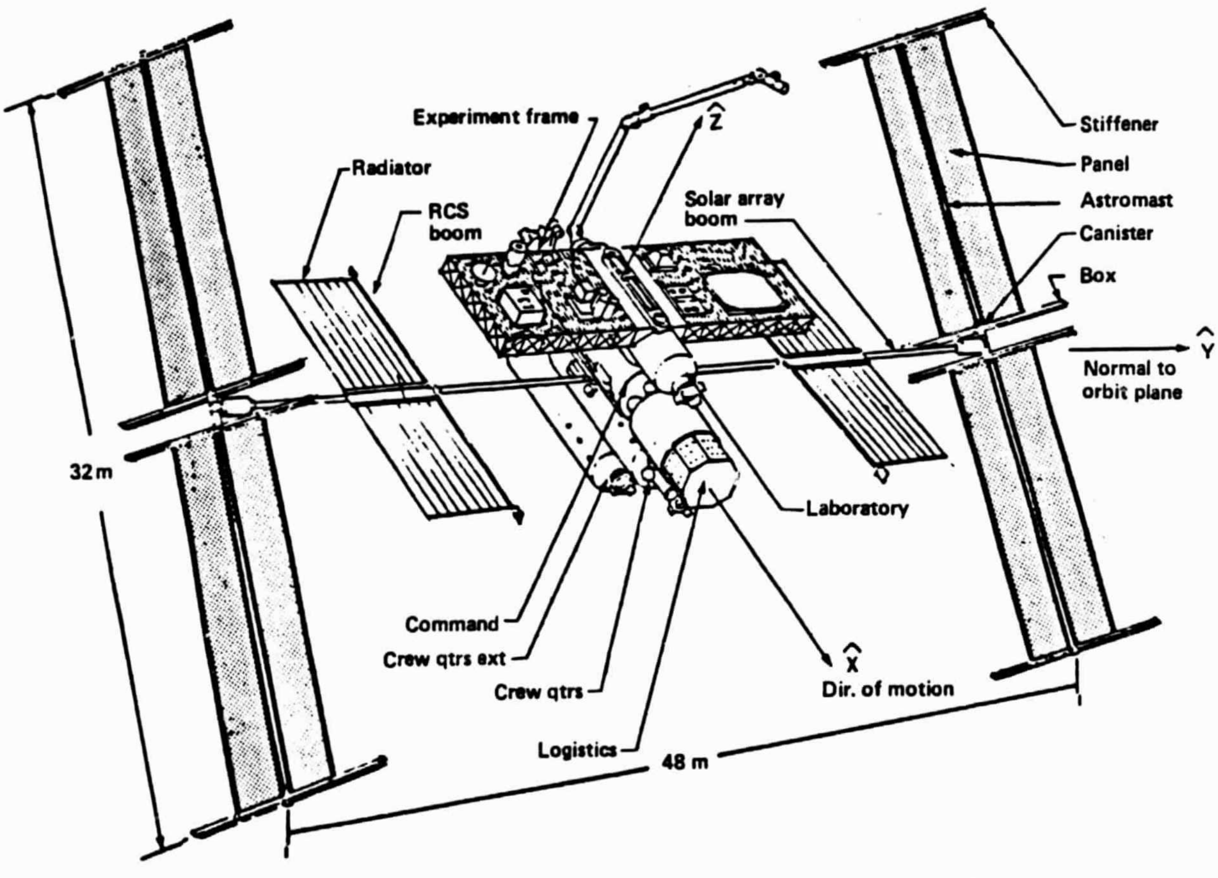


Figure 2.3-2. Balanced Array Concept Astromast Deployment for NASTRAN Analysis

Stiffer solar array structures have been incorporated into the existing elastic simulation model. The objective was to attempt a reduction in the amplitude of the uncontrolled solar panel modes without introducing other serious side effects due to a significant solar panel mass increase.

2.3.2 Technical Discussion

A principal purpose of vibration suppression study is to examine the amount of damping induced in the flexible elements as a matter of course in the positioning of the station and solar panels.

A relative positioning strategy implies that the panels track the sun in elevation and azimuth by commanding a position profile perhaps through a rate command with periodic position updates to account for rate sensor errors. This strategy would use shaft tachometer and position measurements collocated with the actuators as state variables to be regulated. Since the tilt angle for sun elevation has yearly variation, the tilt actuation could be locked and activated only at discrete intervals. If the tilt actuator is locked, some passive augmentation of the panel torsional modes is required. Locking the roll actuator then serves to justify the investigation of passive means of control the uncontrollable panel torsional modes. The relative positioning strategy is reasonable if panel and station pointing requirements are compatible.

An absolute position strategy implies that the panels track the sun in elevation and azimuth by regulating panel attitude through the use of sun sensors. The rate loop could be implemented either by direct rate measurement or a derivation resulting from base (core) rate and shaft tachometer signals. The absolute positioning strategy is reasonable if allowable base motion is far in excess of solar array pointing requirements.

To facilitate the following discussions, a description of the static (panels fixed) configuration indicating the location of all inputs disturbances is provided. In addition, the control system composition for all passive and active controllers is given here for future reference. Accordingly, the location of the control system elements is shown in Figure 2.3-3.

The disturbances profile for modeling crew activity is shown in Figure 2.3-4. The model respresents an astronaut in a soaring maneuver within the Space Station. The motion is envisioned as being a pushoff from one wall and a deceleration on the far wall. The

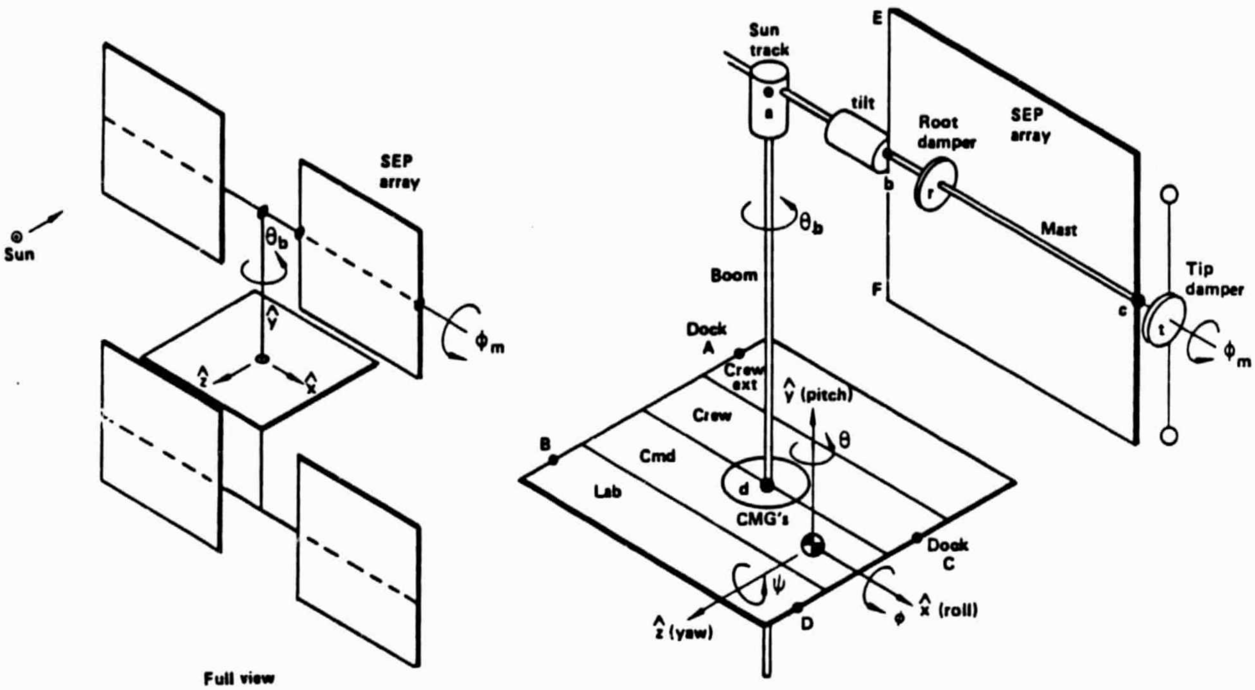


Figure 2.3-3. Loads and Motions With Colocated Linear Controllers

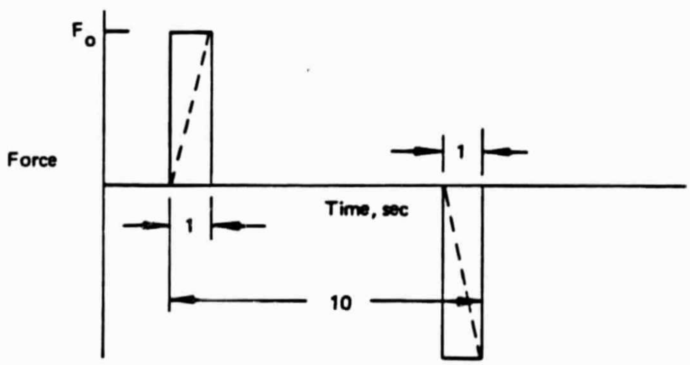


Figure 2.3-4. Disturbance Model for Crew Activity

parameters of the motion are presented for a large astronaut in the flight within a module of about 12 feet in diameter.

A schematic drawing of the Space Station with orbiter docked is shown in Figure 2.3-5. The longitudinal axis of the orbiter is assumed colinear with the yaw axis of the Space Station.

The solar array mast torsional response performance of CMG controllers with root or tip mounted dampers in terms of an impulse response analysis is summarized in Figure 2.3-6.

The root mounted damper was designed to isolate the deployment mast from the base where the solar blanket is attached.

The time histories for the appendage and damper impulse response of the root mounted damper in the controllers for CMGs and actuators for suntrack and tilt are shown in Figure 2.3-7.

The tip mounted damper was designed to provide damping to the panel torsional mode for a reasonable penalty in mass. For a given damper to panel inertia ratio the spring and damping constants were tuned to the natural frequency of the mast. The time histories for the appendage and damper impulse response of the tip mounted damper in the controller collocated with the CMGs are shown in Figure 2.3-8.

Active vibration suppression of both boom and most torsional modes is incorporated in controllers which utilize as a first option a coordinated feedback of relative angular motion variables to the pairwise collocated set of sensors and panel drive actuators. A second option utilizes crossfeeds of absolute angular motion variable to the panel drive actuators in order to decouple base motions from solar panel motions.

Boom and mast torsional response performance of controllers which utilize the first feedback option defined above is summarized in Figure 2.3-9. For this option the tilt actuator was used to drive the base of panel in response to perturbations in panel roll attitude and rate relative to station fixed coordinators measured at the actuator. The control law is sensitive to knowledge of the panel parameters. However, a sensitivity analysis indicated that the degradation in damping due to reasonable ignorance of the panel torsional properties was not severe. The option also uses the suntrack actuator to drive the pivot point of the panel set in response to perturbations in panel pitch attitude

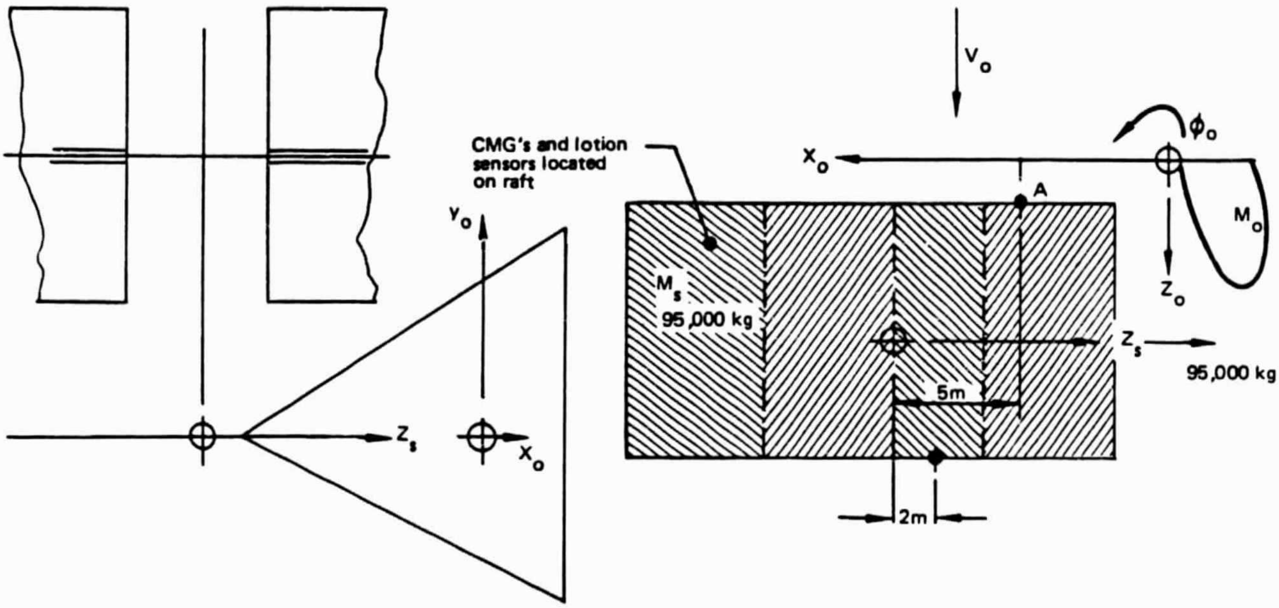
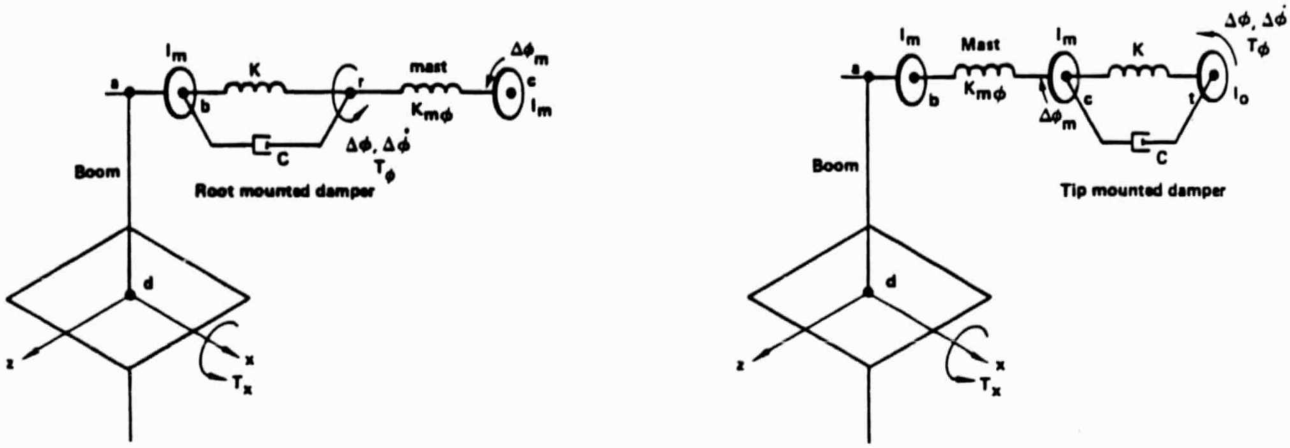


Figure 2.3-5. Berthing Configuration for Orbiter and Disturbance Impulse



Damp loc	Constants		I_o	Peak variables for T_x = 1000 n-m at d			Mast twist	Damping
	K n-m/r	C n-m-sec	I_o Kg-m^2	T_ϕ n-m	$\Delta\phi$ deg	$\Delta\dot{\phi}$ deg/sec	$\Delta\phi_m$ deg	Damping %
Tip	1490	169	768	.10	.082	.027	.05	15
Root	14.90	500	—	.30	.044	.036	.0004	20

Figure 2.3-6. Torsional Vibration Suppression Performance with CMG and Root or Tip Mounted Dampers

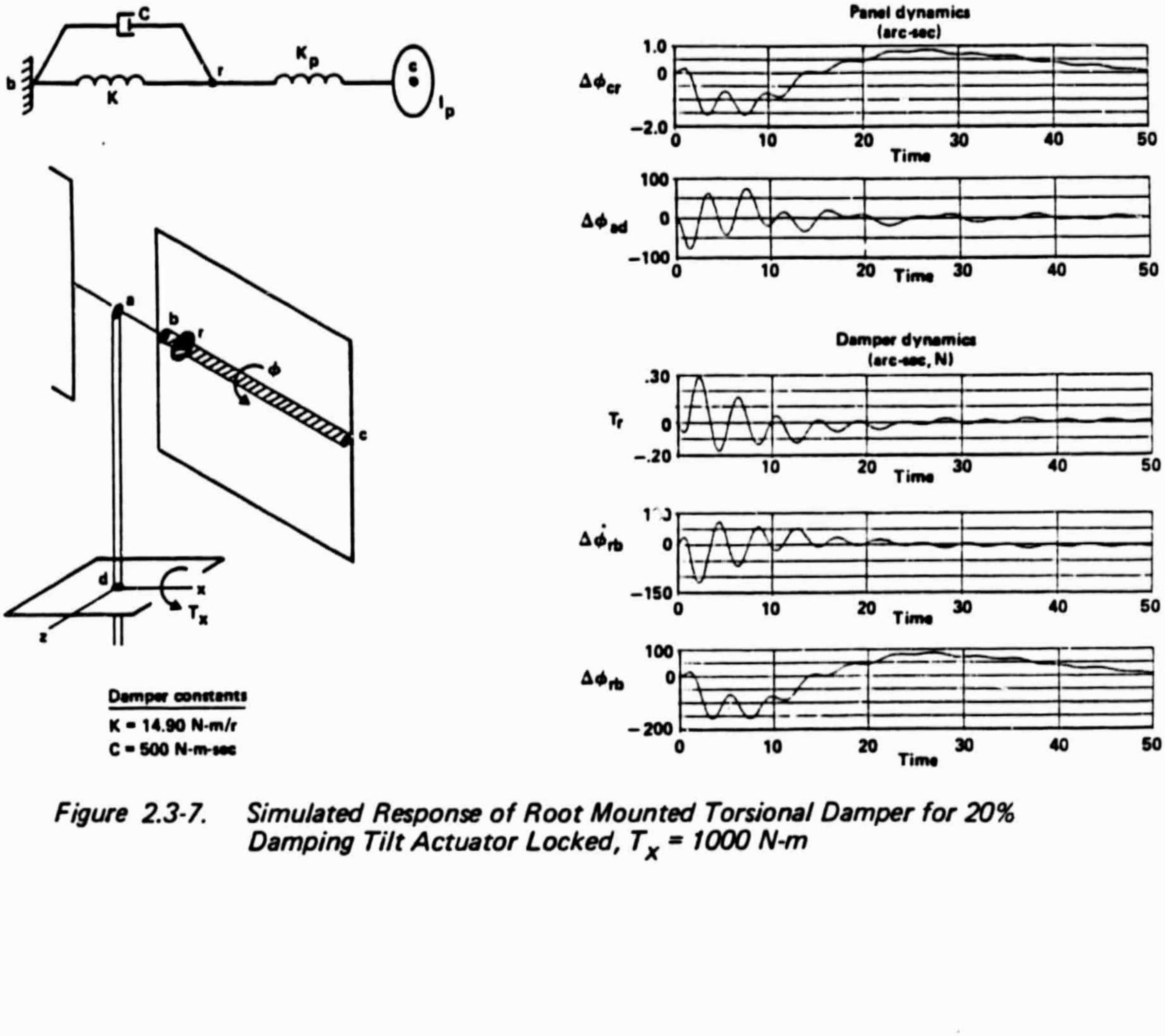


Figure 2.3-7. Simulated Response of Root Mounted Torsional Damper for 20% Damping Tilt Actuator Locked, T_x = 1000 N-m

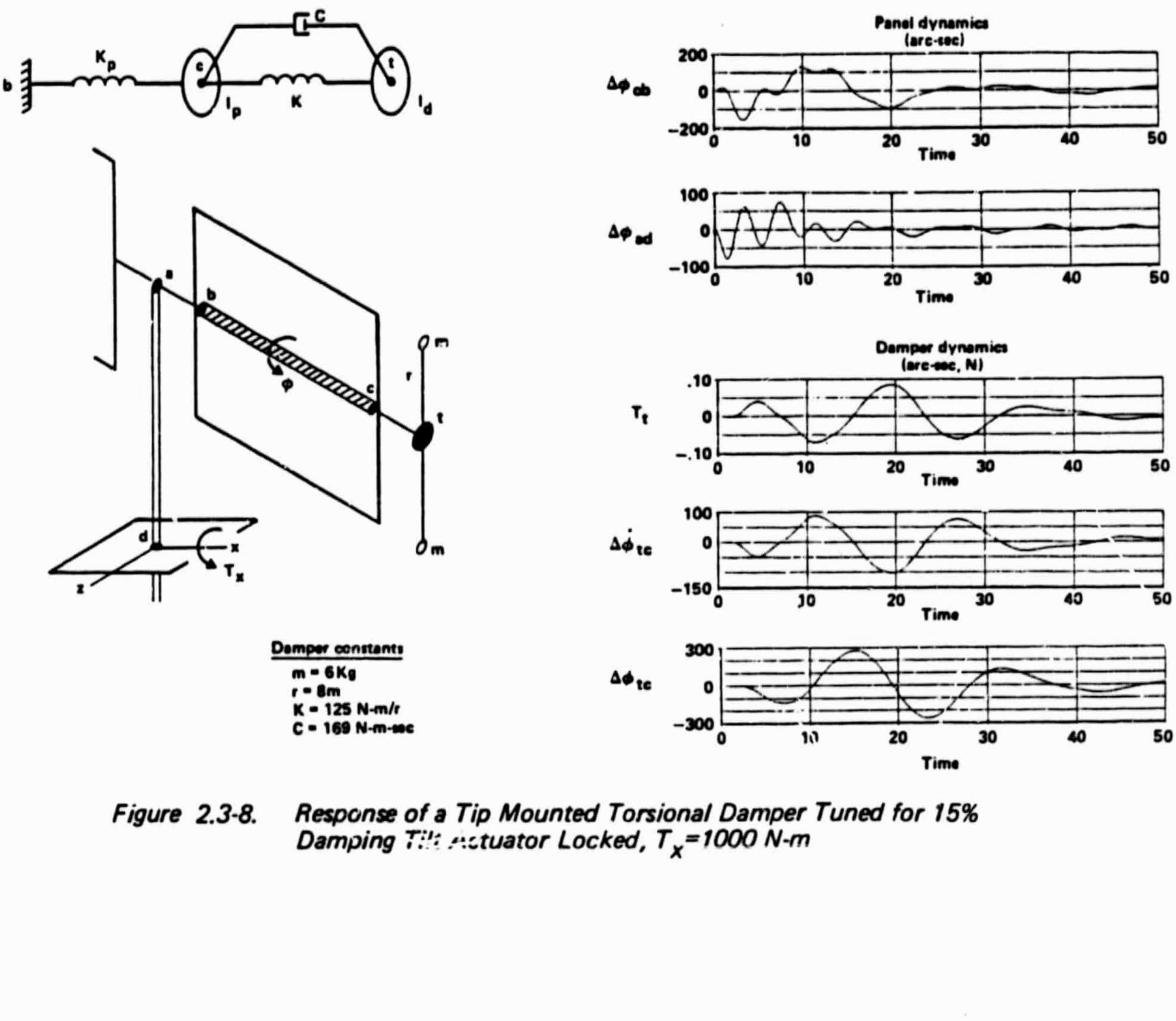
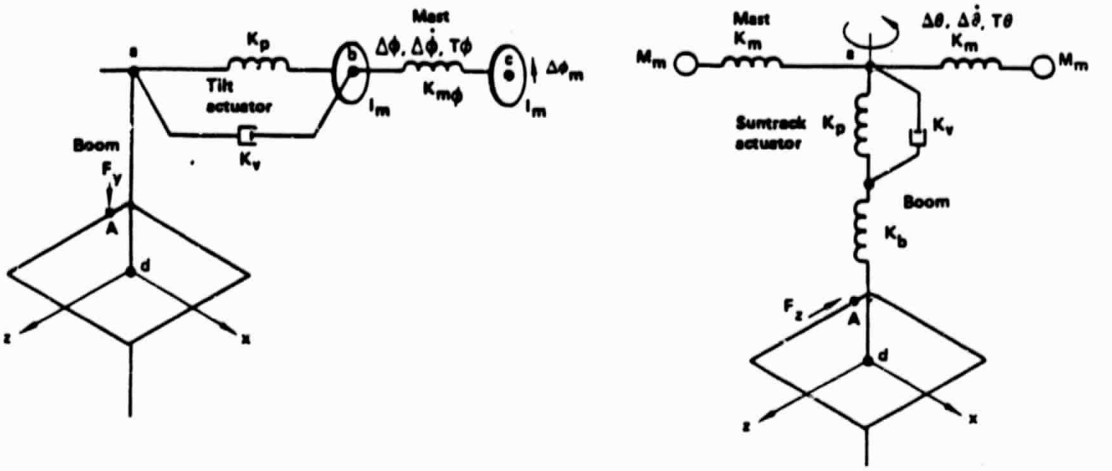


Figure 2.3-8. Response of a Tip Mounted Torsional Damper Tuned for 15% Damping Tilt Actuator Locked, T_x=1000 N-m



Act loc	Gains		Peak control variables for F_y, F_z = 100 n-sec at A			Mast twist	Damping %
	K_p n-m/r	K_v n-m-sec	T_ϕ, T_θ (n-m)	$\Delta\phi$, $\Delta\theta$ deg	$\Delta\dot{\phi}$, $\Delta\dot{\theta}$ deg/sec	$\Delta\phi_m$ deg	
Tilt actuator	1490	6764	.5	.014	.012	.027	43.0
Suntrack actuator	10^4	5×10^4	12	.016	.01[illegible]	–	70.7

Figure 2.3-9. Torsional Vibration Suppression Performance with CMG's, Co-located Suntrack/Tilt Actuators

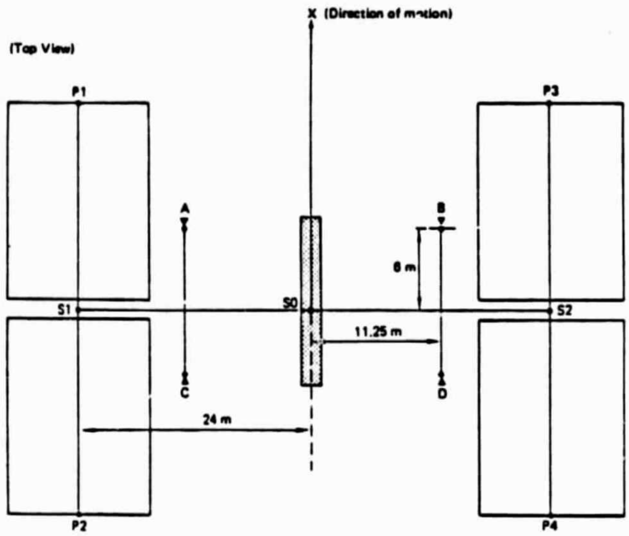
and rate relative to station fixed coordinates measured at the actuator. The controller was designed to provide isolation between the boom and the mast. Tuning of parameters was not required and any level of damping can be achieved.

For the second option identified above, the objective was to apply multivariable control methodology to the given flexible Space Station. Eigenstructure assignment using output feedback was selected for the following reasons. First, output feedback results in fixed gain controllers which do not contain frequency sensitive elements. Fixed gain controllers are easy to implement. Eigenstructure assignment implies that subsets of the modal frequencies and the closed loop eigenvectors can be arbitrarily specified. The size of the subsets depends upon the number of sensors and actuators comprising the controller. Eigenvalue assignment provides modal stability augmentation. Eigenvector assignment allows the closed loop specification of relative motions between various elements of the structure. Finally, eigenstructure assignment theory is a multivariable tool allowing the control system to be synthesized in a single run. However, the theory does not guarantee stability of the closed loop system.

The results of the experiments with eigenstructure indicate that the control objectives are achieved when inertial measurements are implemented. Spatial separation between sensors and actuators on a flexible structure can lead to stability problems. However, the bandwidth of the controller was low enough to provide a stable core and all controllable flex modes were well damped.

The simulation data clearly indicates that appendage translational amplitudes due to symmetric mode excitation from impulse doublet forcing are negligible. However, docking and module berthing shocks could induce significant solar panel motions and attendant central core translation especially for stations with large power requirements. Accordingly, the purpose of the task was to take a quick look at the feasibility of using a propulsion system comprised of resisto jet type thrusters driven by appropriate control logic to damp the translational (butterfly) modes. As mentioned previously, symmetric bending modes are not controllable using torquers unless the panel drives are such that each array can be independently controlled over the two degrees of freedom.

Figure 2.3-10 illustrates the basic simulation configuration used in the analysis of candidate control laws.



Notes:
Sensors at S1, S2 $\Delta\dot{\psi}$, $\Delta\phi$ and $\Delta\dot{\psi}$. $\Delta\dot{\phi}$ relative to S0 (arc-sec)
Sign check of $\Delta\psi$. $\Delta\phi$ at S1, S2 identifies symetric modes
Rate limits on $\Delta\dot{\psi}$ = .25 arc-sec/sec
$\Delta\phi$ = .50 arc-sec/sec
Thrust limit = .13 N

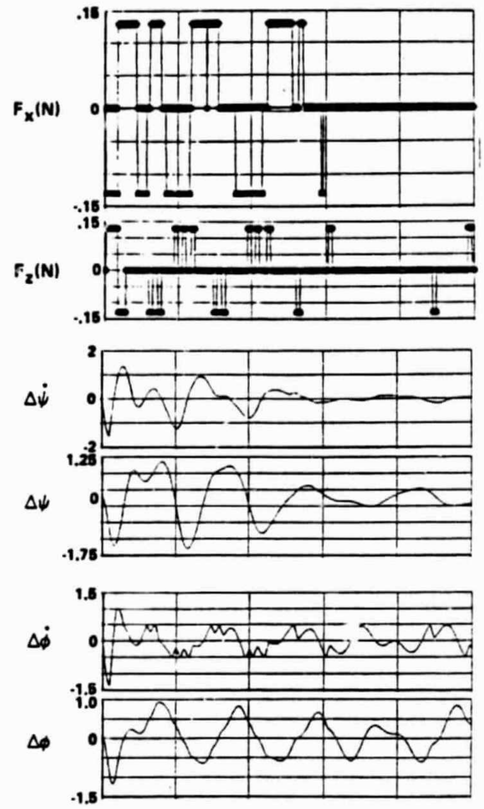


Figure 2.3-10. RCS (Resisto Jet) Control of Symmetric Bending Modes Response to 1000 N-m-sec Torque in Pitch

As the Space Station solar arrays rotate 360° about y-axis to track the sun, it would be difficult to fire the RCS thrusters and not excite the solar array bending modes. However, if some RCS thruster chattering is permissible, then the thrusters can be used to effectively damp the transverse symmetric modes of the solar array boom.

The preceding discussions clearly indicated that vibrations induced in very flexible solar array structures can be easily managed by employing simple techniques with component hardware currently in existence. However, the question remains to determine the controllability of solar panels with improved stiffness. The problem is to compare the structural motions of the SEPS type array with the stiffer arrays assuming panel drive actuators locked.

A solar panel design of current interest at Boeing is shown in Figure 2.3-11. The design features a substrate backed by a lightweight waffle grid structure. The waffle grid adds the required stiffness. The panel sections are foldable in accordion fashion with tapered thickness. The dynamic characteristics are improved due to the extent that the first bending mode is 1.05 Hz. Packaging is less efficient than the SEPs type array and the increase in mass required to obtain the given improvement in first mode frequency is about twice the SEPS array mass.

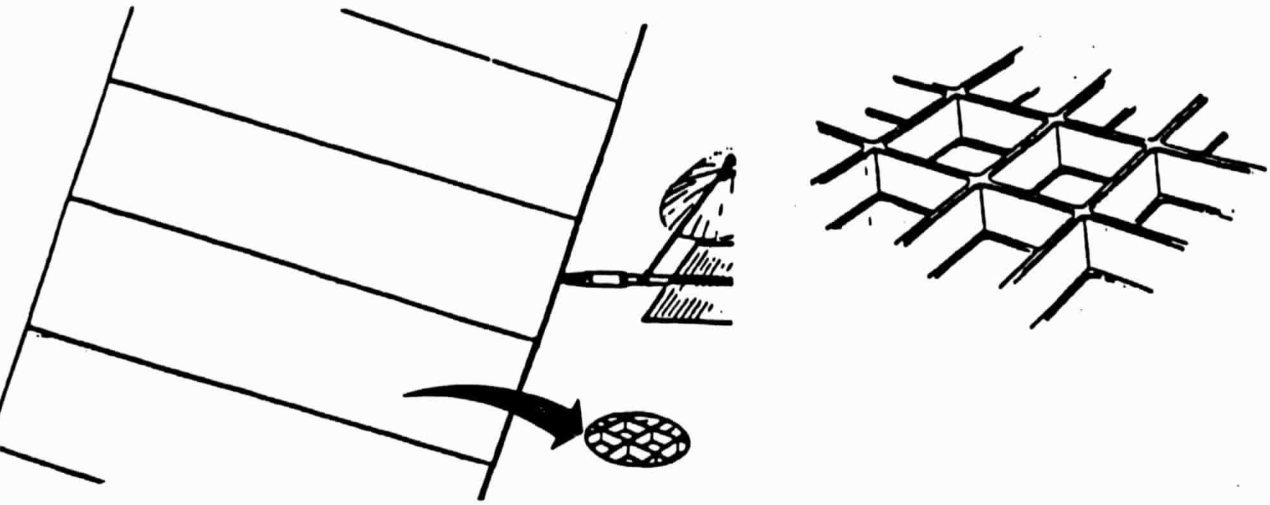
The simulation results using models of these stiffer arrays indicate that the most severe motion is in pitch, manifested primarily as symmetric boom twist and bending. Symmetric torsion in the boom is mildly augmented by CMG control, which is required for some damping in pitch. Panel roll axis torsion and accompanying vibrations in the supporting structure were found to be negligible.

2.3.3 Summary of Results

The issues relating to attitude control impact from structural dynamic motions for a planar space station configuration have been addressed. The following statements summarize the findings of the study.

For SEPS arrays with locked panel drivers:

- o Dedicated vibration suppression is required for solar array torsional modes.
- o Results based on worse case ad hoc disturbance model.
- o Stability guaranteed at control bandwidths of interest.



- Substrate backed by lightweight waffle grid structure
- Foldable panels with tapered thickness
- Improved dynamic characteristics (first mode frequency = 1.05 Hz)
- Packaging less efficient than SEPS type solar array
- Mass increase over SEPS type by 2.5

Figure 2.3-11. Waffle Grid Solar Panels

Control law considerations with SEPS arrays are:

- o Collocated (coordinated) control of station and solar panels provides both rigid body attitude regulation and vibration suppression.
- o Decoordinated control provides the added benefit of panel/station motion decoupling, introducing potential for instability.
- o Dedicated (RCS) control of symmetric bending modes not required for the planar balanced configuration.
- o Simple RCS symmetric bending mode damper with antisymmetric discriminator is effective and feasible.

Active control considerations with SEPS arrays are:

- o Use of panel drive servo actuators is effective and feasible.
- o Current SOA relative motion sensors are adequate.

Passive control considerations with SEPS arrays are:

- o Root mounted damper best choice for mast isolation, least sensitive to parameter variations.
- o Mechanical design may be difficult to implement due to small motions.

Stiff solar array motions with locked panel drives:

- o Use of waffle design (or equivalent) could eliminate need for dedicated vibration suppression controllers.
- o Mass increase by 2.5.

2.3.4 Conclusions and Recommendations

The conclusions for this study area are summarized under paragraph 1.1.2 of this report volume. Continuing effort is recommended in attitude control for space station and that effort should concentrate on defining functional requirements for rigid body control of a dynamically evolving Space Station. The findings of this study, or equivalent, should be used to estimate the effects of flexibility and to assess the need for dedicated vibration suppression systems.

2.4 CONTROLS AND DISPLAYS FOR OMV, OTV & SPACECRAFT SERVICING, FLIGHT OPERATIONS & FUNCTIONAL OPERATION

The area of controls and displays is a new one to the Space Station Systems Technology Study. It was selected as an area of concern due to its inherent complexity, numerous interfaces and vital function to the safe operation of Space Station. The rapid advancement of control system technology could benefit the Station by directing some of the technology advancement to suit its own needs. This effort identifies three areas of technology: (1) those items that will be available for an early Space Station of their own accord; (2) those items that would be available for an early Space Station if pushed; and (3) those items that would be available at a later time. A cost/benefit analysis of the various technologies was also part of the study.

2.4.1 Approach

The objective of this study was to define OMV workstation technology requirements in order to (1) determine any open technology issues unique to Space Station, (2) identify potential benefits and risks associated with the development and use of advanced technology, and (3) develop an implementation plan for advancing those technologies. The following paragraphs present the methodology used to define the workstation configuration and required technology. Summarily, an operational scenario was developed and a functional analysis of the individual tasks was performed. From this analysis, optimal solutions for task implementation in terms of workstation configuration were determined. Technology identification and cost/benefit trades were then performed.

Prior to designing the workstation, we had to understand the functions that had to be accomplished through the controls and displays (C&D) suite. An operational scenario was developed for an OMV controlled from the Space Station and included checkout, launch, rendezvous, docking, return and retrieval mission phases.

The scenario was then used as the basis for a functional analysis of the required tasks. Through the functional analysis, we gained a solid understanding of what tasks needed to be accomplished simultaneously and what information was required to accomplish the tasks. Also, priorities were assigned to the data display requirements.

A literature review of past and current research on control and display technology and implementation was conducted. The purpose of this review was to determine any potential benefits or problems with the various technologies and their implementation based on fellow researchers' experiences.

Two workstation configurations were then developed to satisfy the scenario functional requirements and to provide for efficient operations.

The unique conditions of Space Station and the scope of hardware and software required to implement the workstations led to some innovative technologies. These technologies included flat panel displays, programmable switches, hand controllers, speech recognition, voice synthesis, and touch input devices. Various options within each technology were evaluated and traded against compliance with Space Station needs.

2.4.2 Technical Discussion

The mission scenario defined the limit of operational tasks that would be considered and the order of those tasks. The development of the scenario drove out potential sequencing problems, manloading requirements and offered a preliminary look at the operational timeline. The development of the scenario was based on previous OMV experience.

The scenario was limited to the control of one OMV on a rendezvous and docking mission, including checkout, launch and retrieval upon return to Space Station. The mission scenario was broken into phases as shown in Table 2.4-1. Below each major mission phase heading are listed some of the tasks at the gross level for that phase. This initial step in the scenario development served as the basis for further refinement in the functional analysis.

A summary flow diagram of the completed scenario is shown in Figure 2.4-1. It is keyed to the detailed listing of the functional analysis presented in Table 2.4-2. The numbers in the bottom of the boxes correspond to the numbering system in the functional analysis. The flow diagram provides an overview of the sequence of events while the analysis provides the details of how the tasks are accomplished.

DoD, NASA, and Boeing documentation was searched to locate related research topics.

Table 2.4-1. OMV Mission Scenario by Mission Phase

1.0 Prelaunch checkout (requires C&D and EVA operators)

- Power-up OMV (C&D)

  Check OMV subsystems using BIT through umbilical (C&D, EVA)
  - Power, fuel, thrusters, video docking, apparatus, radar, communications, computers, GN&C, etc.
- Complete OMV visual inspection (EVA)

2.0 Move to launch position (requires C&D and EVA operators)

- Disconnect umbilical (EVA)
- Grapple with RMS (C&D)
- Using RMS, move OMV to launch position (C&D)

  (*may want windows to check position*)
- Check thrusters if not done previously (C&D)
- Check any subsystem necessary (C&D)
  - Nav program loaded into computer
  - Select manual control
- Complete power-up sequence (C&D)

  (Radar, Star scanner, etc.)

3.0 Launch OMV (requires C&D operator)

- Fire GN_2 thrusters to move away from Space Station TBD ft
  - When at TBD ft switch to AUTONOMOUS CONTROL
  - Set up subsystem monitoring configuration

    (*may require two C&D operators to monitor functions*)

4.0 Rendezvous/dock/repair/retrieve (requires C&D operator)

For docking, repair and retrieving:

- Automatically stop at TBD ft from target spacecraft
- Select manual control, GN_2 RCS, cameras, lamps, range sensor, etc.
  - Locate target with cameras and focus, adjust aperture, etc.
- Close on target using GN_2 RCS
- Extend grapple fixture
- Dock with target and soft latch
- Complete hard latch

For repairing only:

- Extend Robotic arm, remove ORU from target and store on Free-Flyer
- Remove ORU replacement and position on target
- Stow arm

Table 2.4-1. OMV Mission Scenario by Mission Phase (Concluded)

5.0 Return to Space Station (requires C&D operator)
Without target spacecraft attached: • Unlatch from target spacecraft • Use GN_2 to back up from target With target spacecraft attached: • Turn off cameras, lamps, range sensor, and associated equipment • Turn on ΔV and MMH RCS • Set in return course • Reset to AUTOMONOUS CONTROL • Stop at TBD ft from Space Station • Turn on/off pertinent subsystems • Switch to GN_2 RCS and manual control • Maneuver to RMS pick-up point and stop
6.0 Berth Free-Flyer (requires C&D and EVA operators)
Without target spacecraft attached: • Grapple using RMS (C&D) • Power down, turn off propulsion (C&D) • Using RMS, move into Containment Area (C&D) • Place in position and connect umbilical (EVA) • Download computers (C&D) With target spacecraft attached: • Unlatch OMV from target spacecraft (C&D) • Grapple target spacecraft wtih RMS and move into Containment Area (C&D) • Grapple OMV with RMS and move into Containment Area (C&D) • Place in position and connect Umbilical (EVA) • Download computers (C&D)

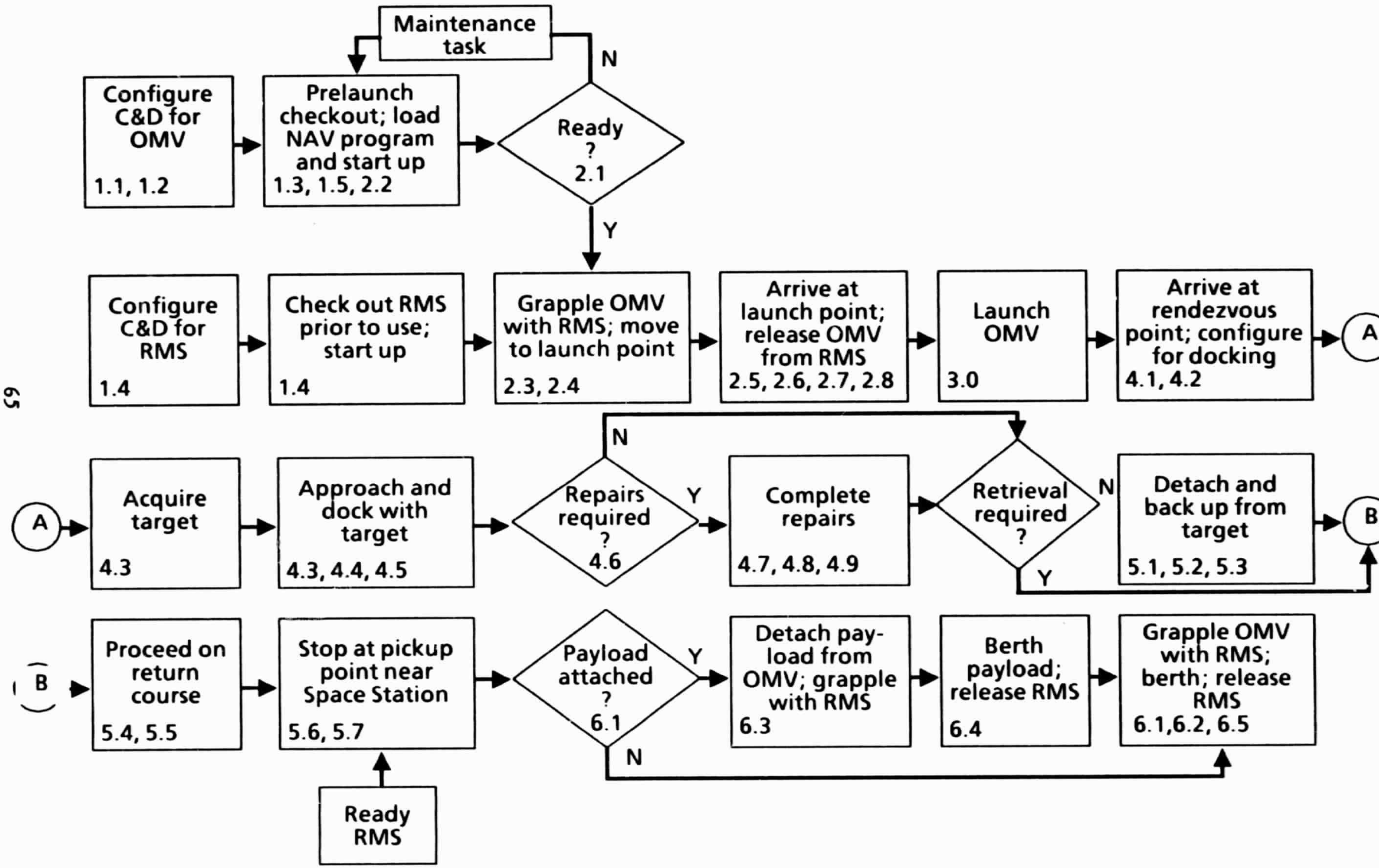


Figure 2.4-1. Mission Scenario Overview

Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 1.0 Prelaunch

Event	Pilot	Copilot	Computer	OMV	Comment
1.1 Configure Controls and Displays (C&D) for OMV Operations (Ops)	Select OMV Ops		Main Function Menu on Display OMV menu up • Other C&D configure according to preset design • Menu allows selection of mission phase and access to appropriate pages		
1.2 Configure C&D for Checkout (C/O)	Select Prelaunch Checkout • Enter vehicle ID #		1st p. of Prelaunch (PRLCH) C/O • Appropriate C&D ready to configure for C/O • List of subsystems available for C/O on 1st p. • If there is a specific sequence to follow, system won't allow any other unless specifically overridden • First is visual inspection	– OMV connected to umbilical – Provides heater power and COMM link	Need alphanumeric pad, enter, clear, delete, etc. keys First action is visual inspection

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Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 1.0 Prelaunch

Event	Pilot	Copilot	Computer	OMV	Comment
1.3 Visual Inspection A. EVA or B. Remote	Communicate with EVA crew on their activity Using Containment Area cameras, and controls and displays, inspect OMV exterior. Enter "COMPLETE" when done.		Acknowledges task completed		– EVA crew necessary or – Requires at least 2 cameras or 1 on a robot
1.4 Start up RMS Operations	* 'VISUAL C/O COMPLETED'	– Configure C&D for RMS Ops – select from menu – Complete presented checklist – RMS and C&D ready for ops	– RMS ops selected – C&D configured – Check list presented		
1.5 OMV Subsystem Checkout •	Makes appropriate inputs to system as instructed on displays *Completes C/O		Subsystem sequence is shown to operator and walked through operation. System suggests tolerance limits but pilot has final decision. Apply power to all systems at once or as you go along? Assuming done as you go along. * C/O COMPLETE PRELAUNCH GO/NO GO STATUS	Send status information to SS computer for all inquiries	Probably use graphics for subsystem C/O (easiest for operator to understand) with lists of pertinent tolerances or use color/pattern codes for quick status recognition

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Table 2-4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	OMV	Comment
2.1 Disconnect Umbilical • EVA or • Remote		Communicate to EVA crew to remove umbilical OR Activate Disconnect switch	– * 'UMBILICAL DISCONNECTED' (CP)		EVA crew removes umbilical or Stiff umbilical that retracts
2.2 Configure for Manual Control	Start setting up C&D for OMV manual control – Select from main menu – results of PRLCH C/O available if necessary If not previously done, load in NAV program – Select NAV – Select program load – Enter data – C/O program load		– Configure (P) C&D for OMV manual control	– Power on for appropriate systems	

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Table 2-4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	OMV	Comment
2.3 Grapple OMV with RMS		Using hand controller(s) grapple OMV with RMS • Video plus pertinent information displayed • When aligned, engage snare wires	Video, range, range rate, etc. displayed * 'OMV LATCHED'		
2.4 Move OMV to Launch Position • Direct Vision – Windows		Using same configuration move OMV to launch point with RMS – have HUD on on window	Has plasma or such type display over window for HUD. Graphics include traffic info, predicted & programmed flight path, range and range rate, caution and warnings, etc.		Feasible that size of work area may require RMS to be on a rail and move along to get additional reach
or • Indirect Vision – camera or imaging-type sensor	Help monitor traffic during transition (need to bring up data on one of station monitors - could use a panoramic display)	Must select cameras (RMS wrist camera blocked). Also select which displays video is shown on. Adjust cameras.	– Controls available to select cameras, etc. – Camera configuration selected is illustrated. Parameters selected are displayed		Movement along rail applies whether use direct or indirect vision.

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Table 2.4-2. *OMV Mission Scenario Functional Analysis*

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	OMV	Comment
2.4 Move OMV to Launch Position (Indirect vision continued)		Select prime video and overlay graphics (as on HUD). Move RMS/OMV using controller(s) to launch point.	– On the display selected prime, overlay similar graphics to what was on HUD * 'LAUNCH POINT ARRIVAL'		Feasible that size of work area may require RMS to be on a rail and move along to get additional reach Movement along rail applies whether use direct or indirect vision.
2.5 Check Launch Status	Check last minute details & recheck critical systems. – computer walks operator through checklist.		* 'LAUNCH STATUS' – rundown on various systems. Order is preset. Operator just pages through or calls a particular system up for C/O. * 'LAUNCH STATUS GO/NO GO'	Send status message to SS computer	Pilot now is prime If 'GO' continue
2.6 Unlatch OMV from RMS		Depress switch on hand controller to unlatch OMV from RMS	* 'UNLATCH OMV' (Command sent to copilot) * 'OMV UNLATCHED'		Snare wires untwist & end effector retracts

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Table 2.4-2. ɹMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	OMV	Comment
2.7 Stow RMS		Using hand controller(s) plus direct or indirect viewing, stow arm	* 'RMS STOWED'		
2.8 Select Attitude Hold (need to do this prior RMS release)	Select attitude hold and GN_2 RCS		Access attitude control page – activate attitude hold mode – GN_2 RCS on	– in attitude (& translational hold) – GN2 RCS on – Onboard computers active.	

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Table 2.4-2. OMV Mission

Mission Phase: 3.0 Launch OMV Mission Scenario Functional Analysis

Event	Pilot	Copilot	Computer	OMV	Comment
3.1 Select Launch Sequence	Select launch program from main menu – Select cameras if necessary for viewing departure; <u>or</u> have <u>direct</u> viewing; <u>or</u> have CGI display		*'LAUNCH SEQUENCE' Configure C&D for launch using manual control – must include hand-off to autonomous control If using direct vision, HUD would be great. Planned flight path, range and range rate, traffic (may need one for P and for CP (head-down)	– Systems are ready for launch – Communication system on and operational	
3.2 Monitor Traffic	Also has responsibility communications during this time	While pilot is maneuvering OMV out of SS proximity, monitor subsystem displays and traffic. Also handles communications if necessary.	Subsystem monitoring and display of pertinent info (expert system required for processing and filtering data)		
3.3 Move to Launch Point	Using hand controller(s), move OMV TBD feet from SS				

Table 2.4-2. OMV Mission

Mission Phase: 3.0 Launch OMV Mission Scenario Functional Analysis

Event	Pilot	Copilot	Computer	OMV	Comment
3.4 Final Systems Check	– When at/near TBD feet (launch point) check with CP to make sure systems are go – IF GO –	Prior to release to autonomous control, check to make sure all necessary subsystems are on and operating	Present final checklist to CP before autonomous control command		
3.5 Launch OMV	Hit switch to autonomous control Relieved	Relieved	SS computers (expert systems) will monitor flight and subsystems. Will notify crew of problem (level of problem when crew notified must be decided). Status available on call by crew.	– Onboard computers will handle flight to rendezvous point. – In continuous communication with SS computers for monitoring and status checks (use of SS expert systems)	

Table 2.4-2. *OMV Mission Scenario Functional Analysis*

Mission Phase: 4.0 Rendezvous/Dock

Event	Pilot	Copilot	Computer	OMV	Comment
4.1 Arrive at Rendezvous Point			– Signals crew OMV has arrived at rendezvous point	– When approaching rendezvous point, OMV starts slowing down so that it is station-keeping with target spacecraft – Stays in this mode until commanded otherwise by crew	
4.2 Configure Systems	Request C&D setup for controlling docking – Turn on cameras, lamps, docking sensor, etc. and locate target. Adjust equipment as necessary – Select GN_2 RCS	Request C&D setup to monitor systems – Monitor systems	– Configure C&D per requests – Display operational messages	– Continue feedback of status information – Cameras, etc. on and operational – GN_2 RCS on; MMH RCS off	
4.3 Close on Target	Using controller(s) approach target spacecraft. Video data, fuel, range and range rate, flight path, predictive display, etc. displayed.		– Display video and other data.	– Transmit video and flight status data	

Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 4.0 Rendezvous/Dock

Event	Pilot	Copilot	Computer	OMV	Comment
4.4 Extend End Effector	– At 10 ft. from target, request extension of end effector to full-out position – Continue closing following flight plan		– Have graphics overlay of flight plan incorporated in display	– End effector moves to fully extended position	
4.5 Dock – Soft & hard latch	Align end effector over grapple fixture – When within docking distance hit snare wires switch to rotate wires – Activate hard latch mechanism – Turn off cameras, lamps,. etc. as necessary		* 'SOFT LATCH' * 'HARD LATCH'	– Snare wires rotate around grapple fixture and secure it. Jack screws then pull in target to soft latch – Target is hard latched to OMV – Cameras, etc. off as requested	
4.6 Configure System for Repair	Request repair mode	Monitor systems	Reconfigure C&D for repair. Hand controller(s) now control robotic arm. Menu up to select functions.	– Robotic arm activated	Assuming use of robot arm on OMV

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Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 4.0 Rendezvous/Dock–Repair

Event	Pilot	Copilot	Computer	OMV	Comment
4.6 Configure System for Repair (Continued)	– Turn on arm camera(s), etc. (Possible use of OMV cameras) – Adjust camera(s) as necessary	Monitor systems	– Send signal to turn arm on	– Arm camera(s), etc. on – Camera(s) adjusting	Need a control to open and close grip on arm. Maybe use a spring-loaded hand grip
4.7 Remove Target Spacecraft Orbit Replaceable Unit (ORU)	– Move arm to new ORU and using grip remove from OMV – Place new ORU in designated slot on target spacecraft; release grip; redo fasteners and connect cable	– Power up and checkout ORU	– Continue to display video, etc.	– Arm continues to respond	
4.8 Replace Target Spacecraft ORU	– Move arm to target ORU, undo fasteners and using grip remove ORU and disconnect cable – Place ORU in designated slot on OMV; release grip	– Power up and checkout ORU	– Continue to display video, etc.	– Arm continues to respond	
4.9 Stow Arm	– Move arm to stow position and secure – Turn off arm and appropriate systems		* 'ARM STOWED AND SECURED'	– Arm stowed and secured – Arm power off, camera(s), etc. off	

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Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	OMV	Comment
5.1 Configure C&D for return trip	Select Return from menu		– Display main menu and highligh selection – 1st page of Return up – C&D reconfigured		
5.2 Unlatch from target spacecraft	Unlatch OMV from t..get spacecraft		* 'UNLATCHED'	– Unlatched from target spacecraft	For nonretrieval mission
5.3 Move away from target spacecraft	– Select GN_2 RCS – Turn on camera(s) radar, etc. so can keep track of progress – Using hand controller(s) back up TBD ft from target spacecraft		– Display video, range, range rate, etc.	– GN_2 RCS on – Camera(s), etc. on – OMV backs up from target spacecraft	For nonretrieval mission Continues same as retrieval mission (on next sheet)
5.4 Turn equipment on/off	– Turn off camera(s) lamp(s), laser ranger, etc.; turn on V and MMH RCS, rendezvous radar	Continue monitoring systems	– C&D available to turn equipment on and off; display feedback status information	– Appropriate systems turn on or off	

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Table 2.4-2. *OMV Mission Scenario Functional Analysis*

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	OMV	Comment
5.5 Program return course	Set in return course. (Expert system could determine what it is and have the course available or another crewmember may determine it and have stored it.)		– Return course set in	– NAV information accepted and activated	
	– Select autonomous control		OMV is released from manual control	– Now under autonomous control of onboard computers	
	Relieved	Relieved	Expert systems will monitor OMV status and progress. Will also alert crew of problems.	– Will alert crew when approaching Space Station. Continue to send status information	

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Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	OMV	Comment
5.6 OMV with or without Payload (P/L) arrives at near stand-off point from Space Station	– Locate OMV visually either directly or by sensors (assuming SS has onboard sensors) – Select GN_2 RCS and manual control	– Monitor systems, traffic and P/L if there is one – Checklist complete	– Receives signal from OMV and alerts crew of its proximity C&D ready for ops. – Display systems checklist on appropriate switch panels	– Onboard sensors determine when at TBD ft from SS and thrusters come on to match SS velocity (stationkeeping) – ΔV & MMH CS off; GN_2 RCS on	
5.7 Maneuver OMV into RMS pickup point	– Using controller(s) maneuver OMV to RMS pickup point; monitor traffic and systems. – Stop OMV at pickup point; put in attitude and translational hold – Start some of the powering down sequence (cameras, radar, etc.)	– Prepare RMS for use – RMS checklist complete	– Configure CP C&D for RMS use – Monitor OMV systems & traffic – Provide for power-down sequence	– Moving to pickup point – Attitude and translational hold on – Systems shutting down	

Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 6.0 Berth OMV–No Payload

Event	Pilot	Copilot	Computer	OMV	Comment
6.1 Grapple OMV	– Monitor subsystems of OMV – Power down rest of system except computer and heater power	Commander now – C&D configured – using controller(s) and HUD (or other such display) move RMS to OVM and align end effector over grapple fixture – hit switch to engage snare wires	– RMS prime cameras, etc. on. – display video and other pertinent data – * 'OMV LATCHED'	– in attitude and translational hold – OMV grapple fixture snared and vehicle latched	OMV now in direct line of sight
6.2 Move to containment area	– Download computers – Shut down	– Using RMS move to containment area and place in 'cradle' – Connect umbilical (provides power and communication link)	– Data transfer	– Quiescent	– Complete

Table 2.4-2. OMV Mission Scenario Functional Analysis

Mission Phase: 6.0 Berth OMV–No Payload

Event	Pilot	Copilot	Computer	OMV	Comment
6.3 Disengage OMV and Payload (P/L)	– Release latching mechanism between OMV and P/L. If necessary, back-up OMV from P/L – Put OMV in attitude and translational hold		– Pilot C&D configured for OMV and CP C&D configured for RMS – *'OMV and P/L DISENGAGED' – RMS up, C&D ready	– OMV and P/L disengaged	
6.4 Grapple P/L and move into containment area		– Using RMS, grapple P/L and move into containment area, placing in cradle. Connect umbilical if necessary			
6.5 Grapple OMV and move into containment area. (Proceed as on previous page)					

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One of the most promising ideas in the literature for information presentation is the use of pictorial formats. This concept relies on the use of graphics and object representation rather than columns and rows of numbers and characters to communicate information. Various pieces of related data are integrated into a single format that is readily comprehended by an operator. In this way, the operator can make better use of decision-making capabilities.

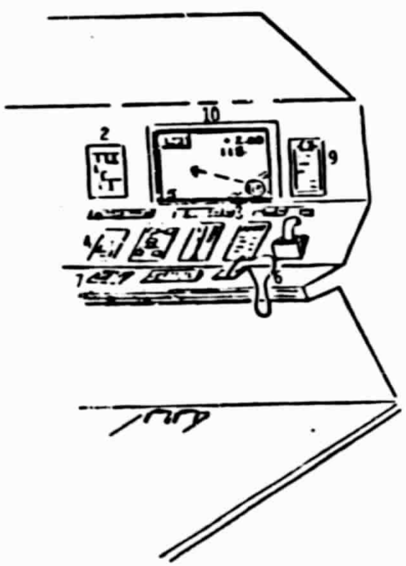
The use of voice both as a means of data input and output is another new promising area. Voice input or voice recognition can be used for many of the same types of tasks that are presently accomplished through a keyboard.

Based on the results of the functional analysis plus the research review and mission scenario, two workstation configurations were designed. The configurations are shown in Figure 2.4-2. The primary difference between the two configurations is the first has a window for direct viewing of proximity operations and the second has no window using indirect or remote vision only. The configurations served to define the number and type of displays and controls, i.e., high resolution, full color graphics displays, 10-inch and 15-inch on the diagonal, are required.

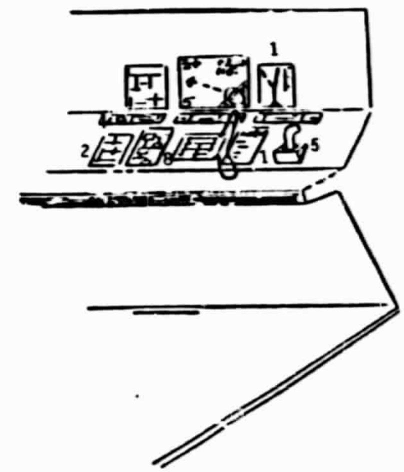
For comparison purposes only, the somewhat outdated display information in Table 2.4-3 is provided. Note that the display technology field has advanced significantly since this information was published.

Flat panel technology is being used in programmable switches in addition to being used for displays. Light-emitting diode (LED), thin-film electroluminescent (TFEL) and liquid crystal display (LCD) technologies are being incorporated into various switch housings for this purpose. The most mature of these is the LED switch which is being developed for both military and commercial aircraft application.

Much research is being done in the area of speech recognition, spurred on by military and commercial applications. The current systems are speaker-dependent and recognize isolated or connected speech. The stored vocabulary size is less than 500 words with approximately 50-75 words available at one time. Training the systems requires three to four passes on each word. Speaker adaptation and identification is limited.



Without Window



Common Features
(1) Multifunciton Displays
(2) Programmable Switches
(3) Caution and Warning Panel
(4) Dedicated Switch Panels
(5) 6-axes Hand Controller
(6) Touch Input Device
(7) Voice Synthesis and Recognition
(8) Keyboard
(9) Clipboard

Unique Features
(10) Head-up Display

Figure 2.4-2. Conceptual Workstation Configurations

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Table 2.4-3. Display Technology Comparison

	Voltage	Power	Colors	Display size	Display depth	Rise time	Fall time	Inherent memory
Cathode ray tube (CRT)	up to 15 kV	$\leqq$ 100W	<20	0.75m diag.	1.2 x diag	1 µs-1 ms	1 µs-100 ms	No
Plasma	115V	400-500 mW/cm^2	<20	2m diag	12 mm	100 ns	2 µs	Yes
Electroluminescent (EL)	30-650V	2-6 mW /cm^2	3	(1.63m)^2	5 mm	1 ms	10 µs-1.5 ms	No
Liquid crystal display (LCD)	1-8 V	1 mW /cm^2	<20	(30 cm)^2	1-2 mm	50-300 ms	100-400 ms	Yes
Light-emitting diode (LED)	1.5 to 5.0V	1.5 mW /elem	3	(0.26m)^2	10 mm	10 ns	10 ns	No

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Voice synthesis is much further advanced than speech recognition. Stored vocabularies can be 10,000 words with some degree of inflection and intonation. Some systems use digitized voice whereas others use phoneme-based speech. Some systems also allow a choice of voice types.

The current technology of head-up displays has achieved a maximum horizontal field-of-view (FOV) of 30°. The combining surface for such a FOV is usually 4-8 inches from the operator's eyes. The operator must maintain their eyes in a fixed position in space in order to view the entire display. These features are unacceptable for this workstation.

Real-time graphics and high-resolution dynamic imagery is feasible with current technology and it is continually advancing. Potential areas of concern with current technology include the size of the machine necessary to generate the displays and its power, volume and weight specifications. However, until the display formats are at least superficially defined, any estimate on machine capacity requirements would be unrealistic.

2.4.3 Technology Candidate Comparisons

Tables 2.4-4 and 2.4-5 describe the technology options that appear most promising and evaluate them further based on a cost/benefit basis.

2.4.4 Conclusions and Recommendations

The conclusions for this study topic are summarized under paragraph 1.1.3 of the report volume. Some issues discussed in this study area are recommended for further research. These issues include:

- o Establish the need for a window at the OMV workstation. If a need is established, the requirements for the window need to be determined such as size and location at the workstation as well as in the module.

- o If a window is found to be required, a Head-Up Display for that window should be developed. Again, the requirements for the HUD need to be determined such as size, location at the workstation, presentation of sensor data, illumination and transmissivity.

Table 2.4-4. *Qualitative Cost/Benefits of Technology*

Technology	Cost	Benefit	Comment
• Flat panel	H	H	Cost is high relative to CRT; great savings in power, weight, and volume; helped by consumer market
• Voice recognition and synthesis	L	H	Cost low due to development for commercial and military markets; great boon to operators
• Programmable switch	L	H	Exist presently; relieve panel space
• Hand controller	L	M	Prototypes exist presently; relieves panel space and one hand
• Input devices (touchpen)	L	M	Exist presently; reduces operator error rate, workload, and time
• Head-up display	H	H	Wide field-of-view would drive cost up; reduces operator workload

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Table 2.4-5. Quantitative Costs/Benefits/Risks of Technology

Item	Cost Δ(%) Devel-op-ment	Cost Δ(%) Pro-duc-tion	Δ (%) Power	Δ (%) Weight	Δ (%) Volume	Development Risks	Benefits
Multifunction display							
<u>CRT</u>							
LCD	+ 3* mil	− 80	− 67	− 93	− 83	Color saturation, resolution, update rates, luminance	Reduced power, weight, volume and production cost. Higher MTBF
Multifunction switch							
<u>LED</u>							
TFEL	+ 35	− 12	− 83	0	0	Color shift with aging, tricolor panel	Reduced power and production costs. Higher MTBF.
LCD	*	− 86	−90	0	0	Color saturation, luminance	Weight and volume savings insignificant due to switch actuator mechanism

* Complementary development costs

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Table 2.4-5. *Quantitative Costs/Benefits/Risks of Technologies (Concluded)*

Item	Cost Δ(%) Devel-op-ment	Cost Δ(%) Pro-duc-tion	Δ (%) Power	Δ (%) Weight	Δ (%) Volume	Development Risks	Benefits
<u>3-Axes Controller</u>							
6 Axes Con-troller	0	+ 25	0	– 50	– 50	Already developed but requires zero-g test	Fewer components; frees one hand
<u>Touch Screen</u>							
Touch Pen	0	+ 25	- 25	0	0	Already developed but requires zero-g test	Reduced accidental activation. Increased accuracy
<u>Voice I/O</u>							
Advanced Voice I/0	+ 1.5 mil	+ 90	0	0	0	Memory requirements and signal processing speed	Reduced training requirements and visual workload. Increased operator performances
<u>30°-FOV HUD</u>							
60°-FOV HUD	?					Technology feasibility	Reduce operator workload and eye fatigue

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- o Development of display formats for vehicle control, system and subsystem information, caution and warning messages and other pertinent data presentation requirements.

- o Refine the mission scenario and workstation design as required. The design developed for this study was primarily a strawhorse to drive out technology requirements.

- o Determine the benefits of using a stereoscopic display of video or computer-generated imagery for the OMV and RMS control tasks. Select a suitable technology for implementation.

2.4.5 Technology Advancement Plans

Advancement plans have been prepared for three technologies related to controls and displays for OMV, OTV and spacecraft servicing, flight operations and functional operations from Space Station work stations. The first, is the development of a head-up display device with a very wide field-of-view (60°) to accommodate an operator at an OMV teleoperator control station. While there is a significant amount of effort being expended in the development of new display techniques, no effort to widen the field-of-view to this extent has been identified in industry or within government agencies. The possible reason is a lack of specific requirement for a very wide FOV version. Typically aerospace needs are satisfied by the side field of view configuration (30°) such as the one that has already flown in the Space Shuttle.

The next two plans cover the emerging technologies in liquid crystal displays. The first is the development of large flat panel displays (8 inch diagonal) using LCD technology to replace CRT screens. The second is the application of flat panel technology to a switch. A single switch would be used for many purposes by programming its function and the label on the switch.

The requirements for and benefits of these technologies in an OMV teleoperations workstations are discussed in detail in volume II of this report. The programs described in Figures 2.4-3 thru 2.4-5 and Tables 2.4-6 thru 2.4-8 summarize the basic technology planning information needed to capture those technologies needed for early evolutionary versions of the Space Station. The detailed advancement planning discussion supporting these summaries is provided in volume III of this final report.

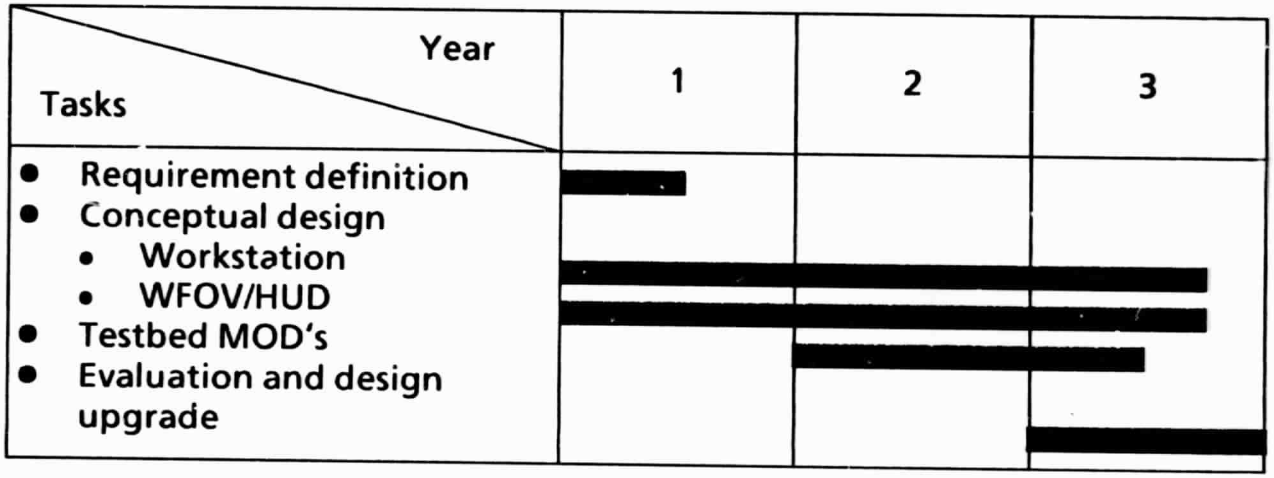

Figure 2.4-3. Schedule for Development of WFOV/HUD

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Table 2.4-6. Resources for WFOV/HUD

Step	Tasks \ Year from ATP	1	2	3	Total
1	Requirements definition	120			120
2	Conceptual design				
	- Workstation	90	60		150
	- WFOV/HUD	270	280		450
3	Testbed modification		290	290	580
4	Test and evaluation			482	482
Total		480	530	772	1782

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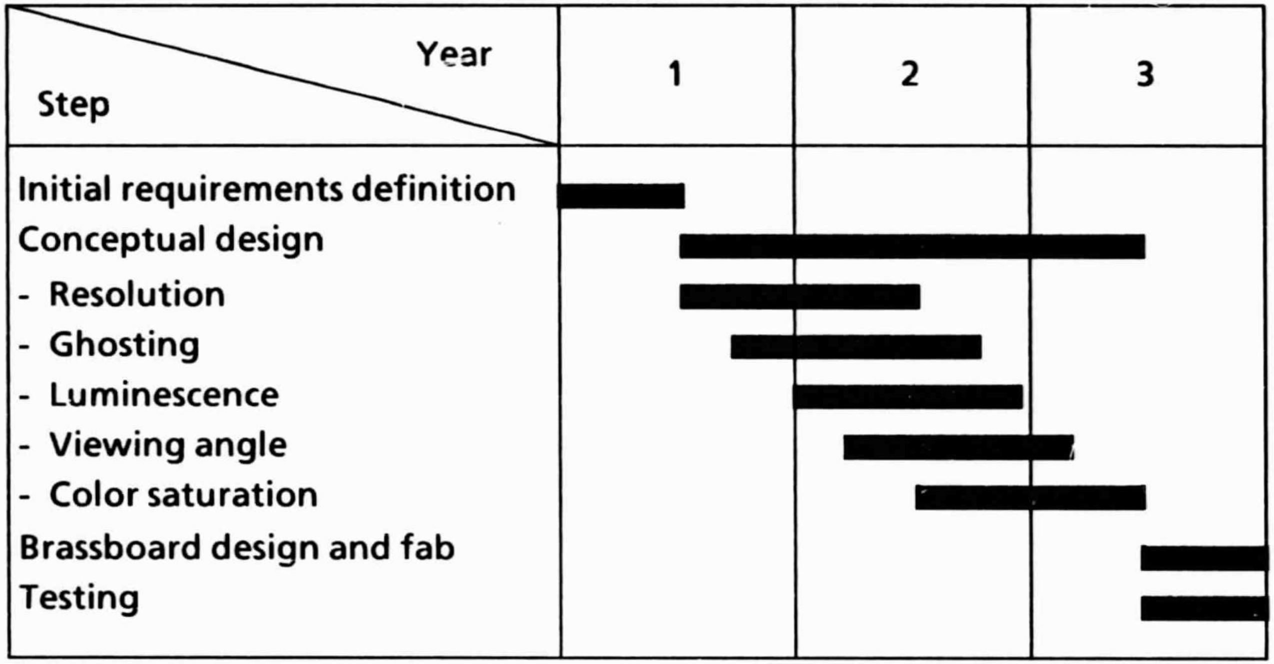

Figure 2.4-4. Schedule for High Performance Color Flat Panel LCD Display

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Table 2.4-7. Resource Requirements for High Performance Color Flat Panel LCD Display

Step \ Year	1	2	3	Total
Initial requirements definition	180			180
Conceptual design				
- Resolution	72	72		144
- Ghosting	36	108		144
- Luminescence		144		144
- Viewing angle		108	36	144
- Color saturation		72	72	144
Brassboard design and fab			205	205
Testing			300	300
Total	288	504	613	1225

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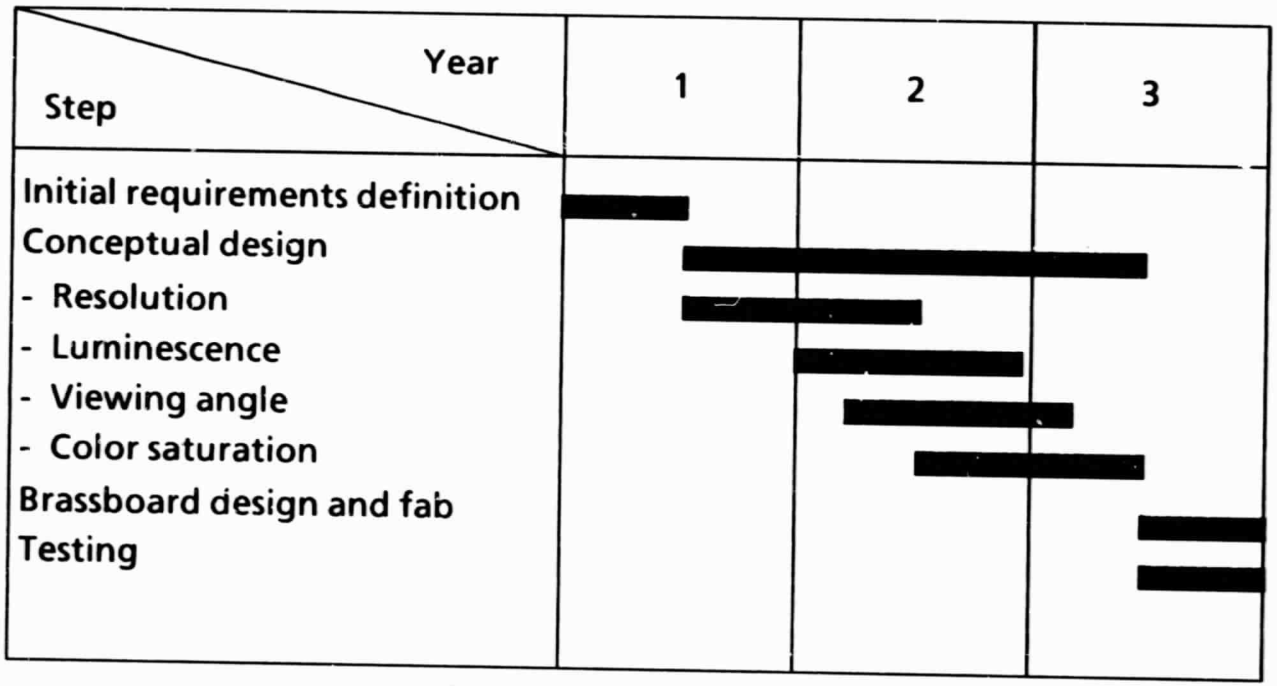

Figure 2.4-5. Schedule for Small High Performance Color Programmable Multifunction Switch

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Table 2.4-8. Resource Requirements for Small High Performance Color Programmable Multifunction Switch

Step \ Year	1	2	3	Total
Initial requirements definition	117			117
Conceptual design				
- Resolution	46.8	46.8		93.6
- Luminescence		93.6		93.6
- Viewing angle		70.2	23.4	93.6
- Color saturation		46.8	46.8	93.6
Brassboard design and fabrication			133.25	133.25
Testing			195	195
Total	187.2	327.6	398.45	796.25

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